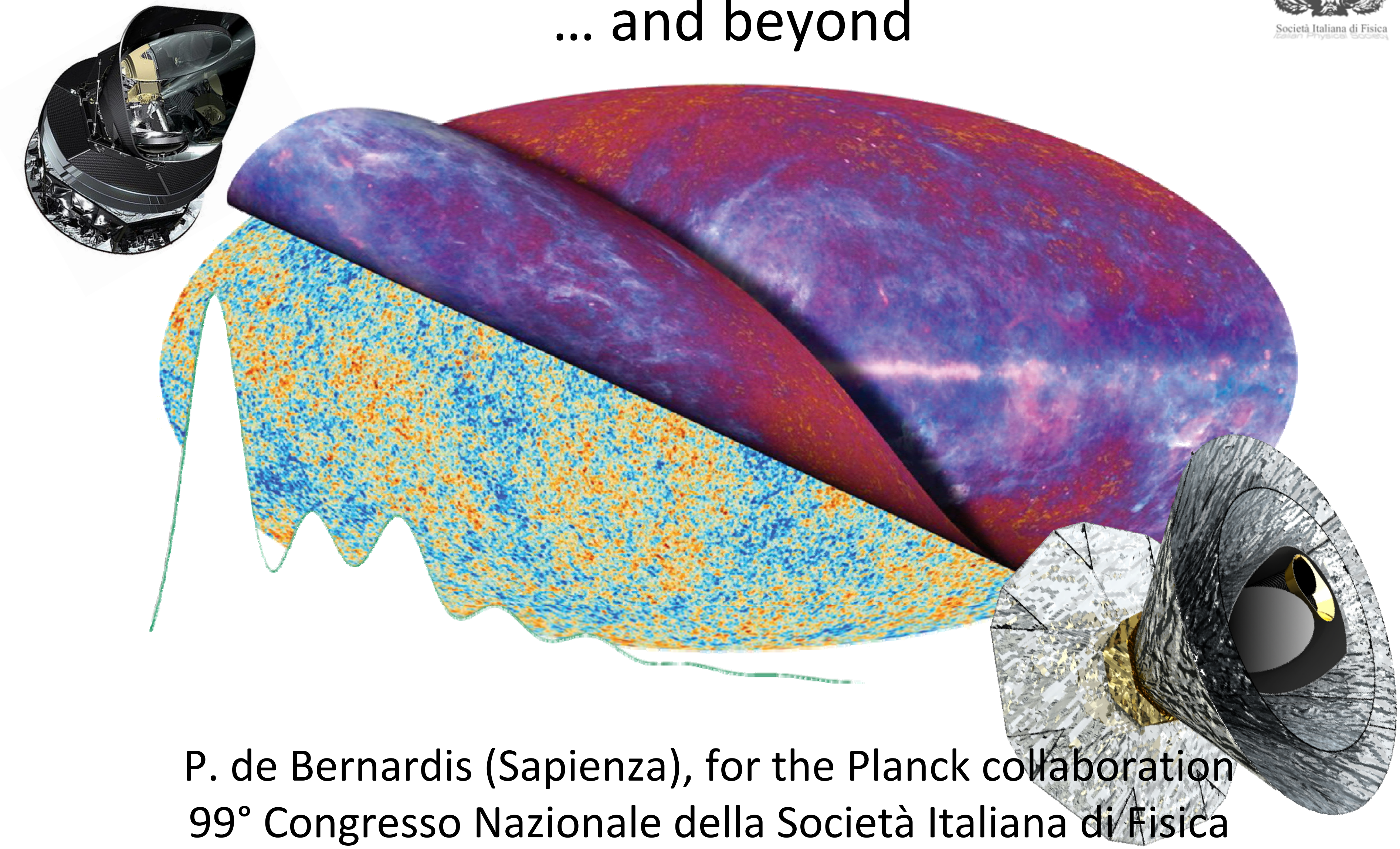
2013 results from the Planck satellite …
… and beyond



P. de Bernardis (Sapienza), for the Planck collaboration
99° Congresso Nazionale della Società Italiana di Fisica
Trieste 23/09/2013

Planck 2013

- The Planck collaboration has released in March 2013 the results of the first 15 months of operation of the Planck satellite.
- 30 papers, more than 1000 pages of A&A
- The most precise observations of the **Cosmic Microwave Background (CMB)** ever.
- Here we summarize the main scientific results, and describe the forthcoming activities in this field.

The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

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planck

cnes

agenzia spaziale italiana

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OPLANCK● LFI

NASA

cnrs

DTU Space National Space Institute

Science & Technology Facilities Council

CSIC

HFI PLANCK

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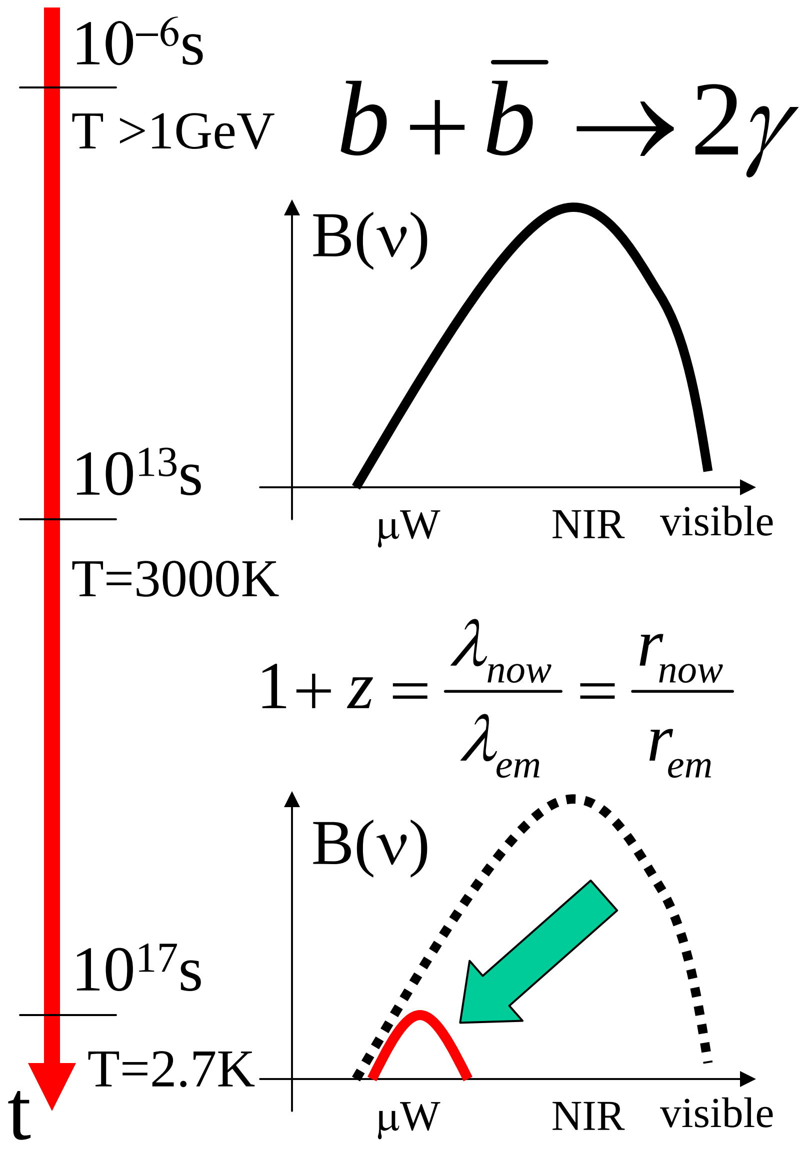
What is the CMB



$$b+\bar{b}\rightarrow 2\gamma$$

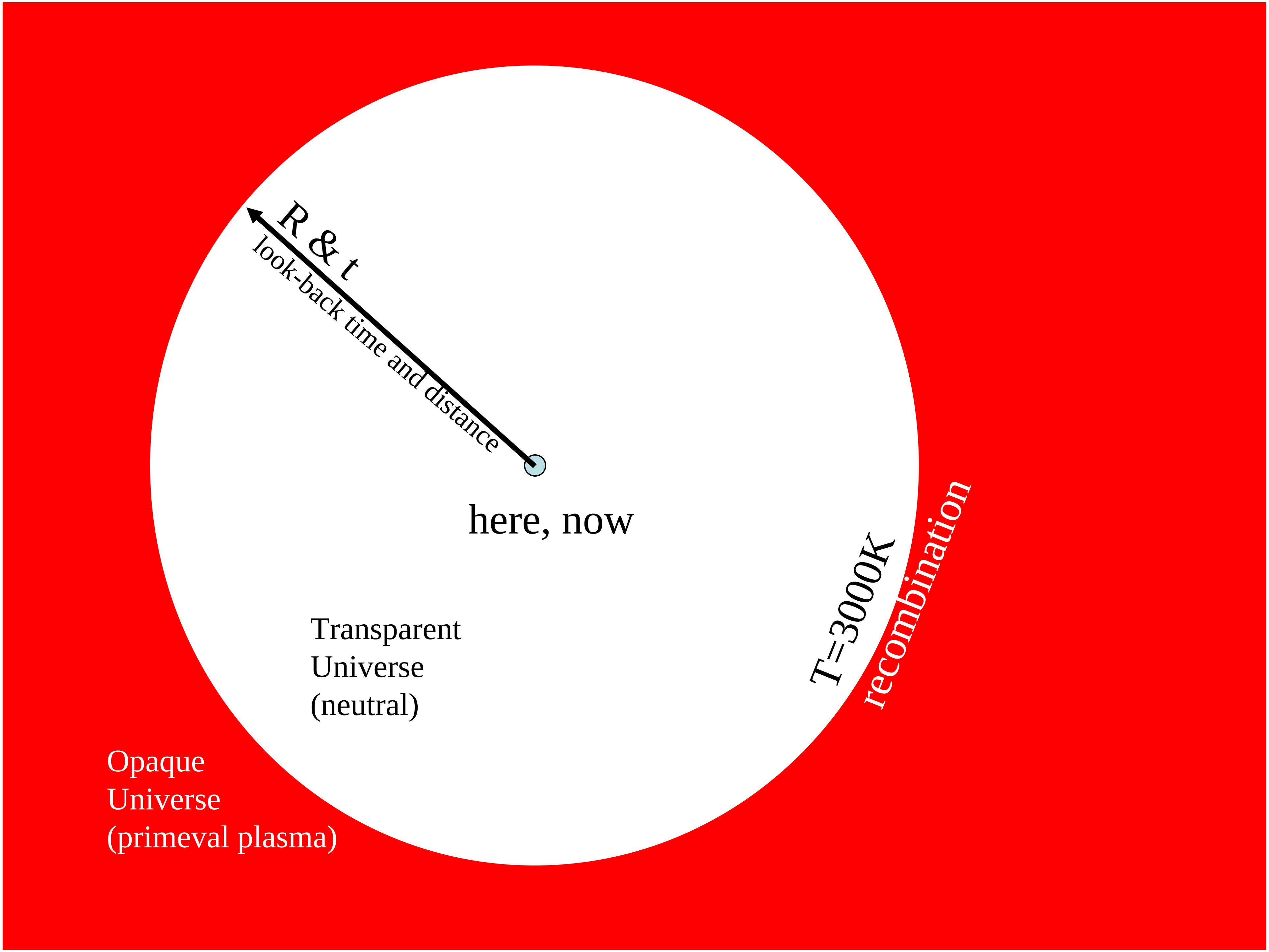
$$1+z=\frac{\lambda_{now}}{\lambda_{em}}=\frac{r_{now}}{r_{em}}$$

According to modern cosmology:

An abundant background of photons filling the Universe.

- **Generated** in the very early universe, less than 4 μs after the Big Bang (10^9γ for each baryon)
- **Thermalized** in the primeval fireball (in the first 380000 years after the big bang) by repeated scattering against free electrons
- **Redshifted** to microwave frequencies **and diluted** in the subsequent 14 Gyrs of expansion of the Universe
- **Today: 410γ/cm^3, ~1 meV**

These photons carry
significant information
on the structure, evolution and
composition of our universe



R & t

look-back time and distance

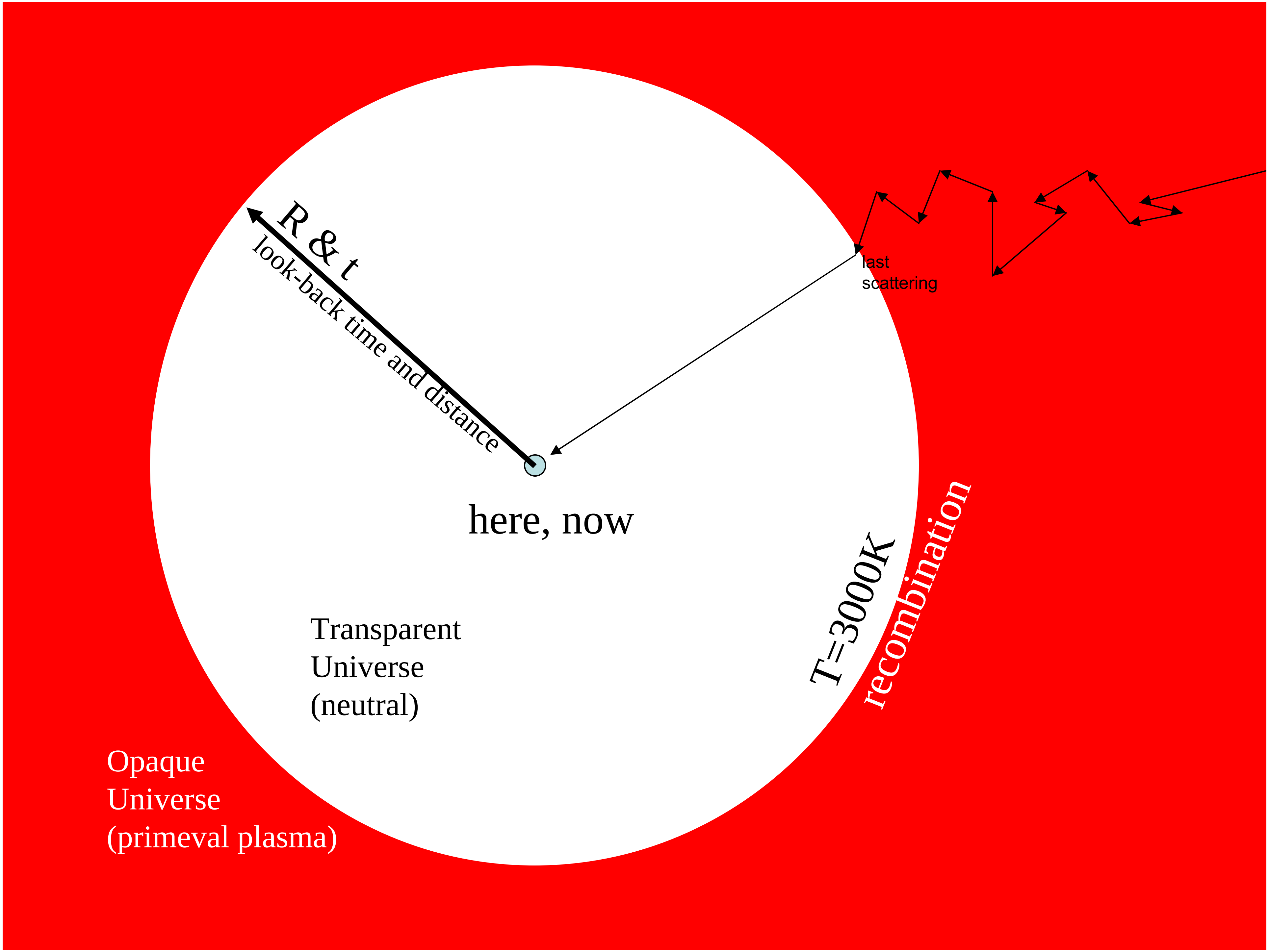
here, now

T=3000K

recombination

Transparent
Universe
(neutral)

Opaque
Universe
(primeval plasma)



R & t

look-back time and distance

last
scattering

here, now

T=3000K

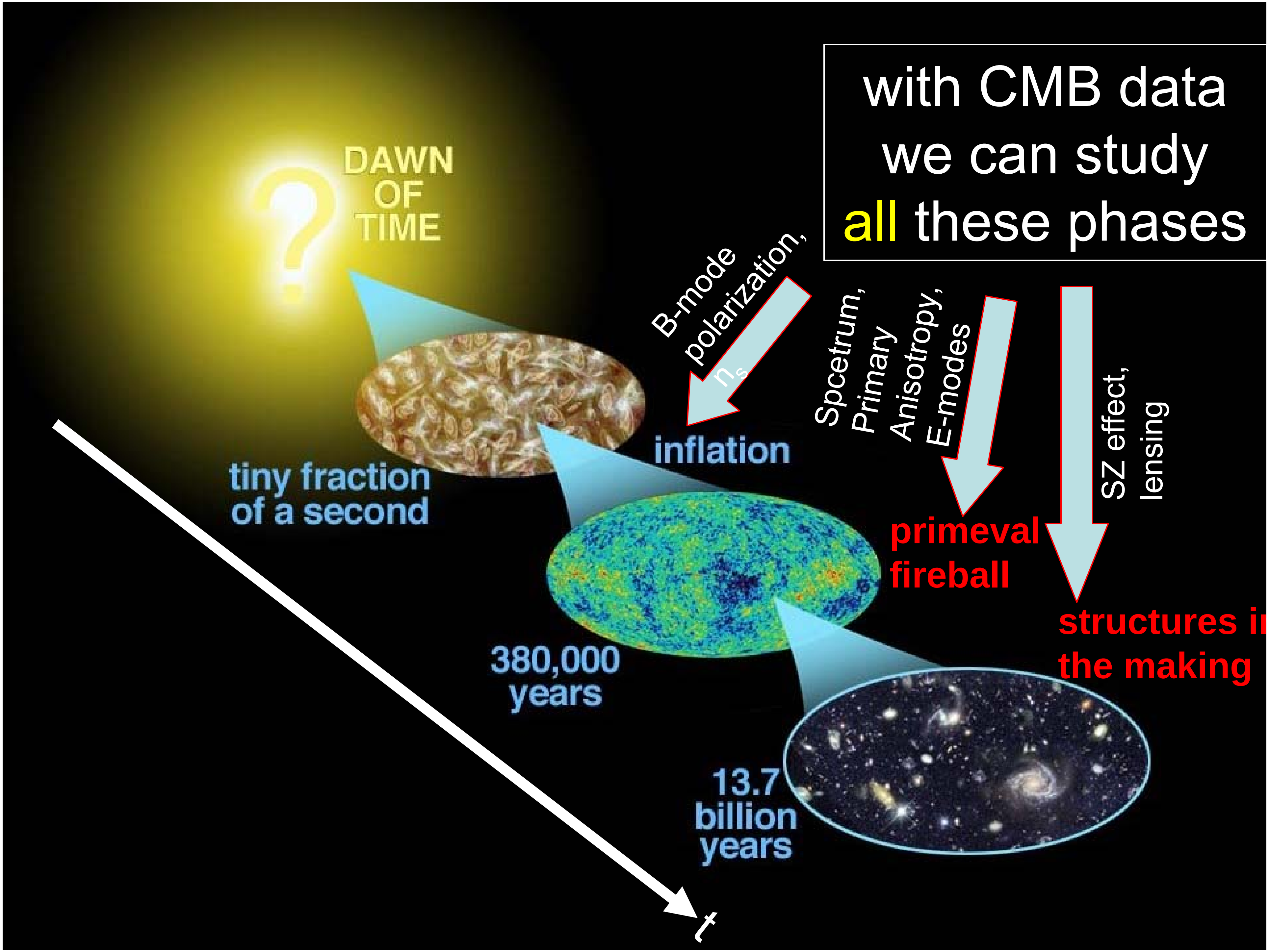
recombination

Transparent
Universe
(neutral)

Opaque
Universe
(primeval plasma)

The spectrum

- CMB photons are produced when matter and radiation are in tight thermal equilibrium (Thomson scattering in the primeval plasma)
- The spectrum of the CMB has to be a blackbody.
- The expansion of the universe preserves the shape of a blackbody spectrum, while its temperature decreases as the inverse of the scale factor.
- Measuring a blackbody spectrum of the CMB, we can prove the existence of a primeval fireball phase of the universe.
- To be consistent with the primordial abundance of light elements, a temperature of a few K is expected (Gamow)



with CMB data
we can study
all these phases

B-mode polarization, n_s

Spcetrum, Primary Anisotropy, E-modes

SZ effect, lensing

primeval fireball

structures i the making

t

CMB anisotropy (intrinsic)

- Different physical effects, all related to the *small* density fluctuations $\delta\rho/\rho$ present 380000 yrs after the big bang (recombination) produce CMB Temperature fluctuations:

$$\boxed{\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\varphi}{c^2} + \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} - \frac{\vec{\mathrm{v}}}{c}\cdot\vec{n}}$$

Sachs-Wolfe (gravitational redshift)

Photon density fluctuations

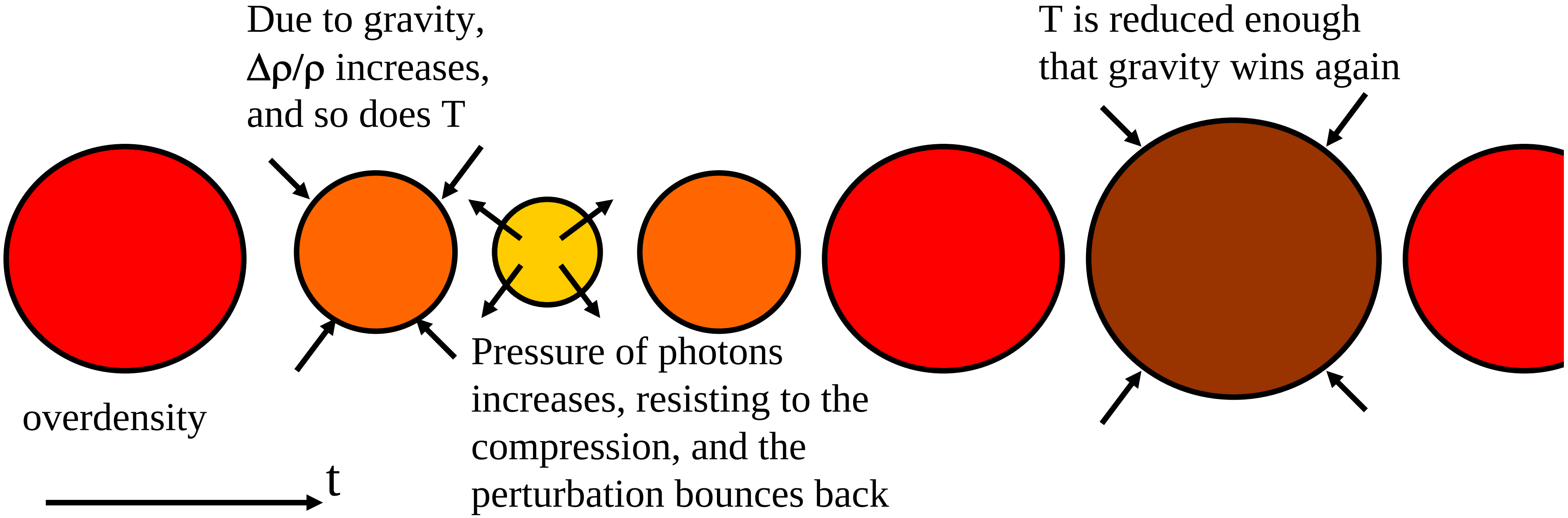
Doppler effect from velocity fields

- Scales larger than the horizon are basically frozen in the pre-recombination era. Flat power spectrum of $\delta T/T$ at large scales.
- Scales smaller than the horizon undergo acoustic oscillations during the primeval fireball. Acoustic peaks in the power spectrum of $\delta T/T$ at sub-degree scales.

CMB anisotropy (intrinsic)

- The primeval plasma of photons and matter oscillates :
- self-gravity vs radiation pressure.
- We can measure the result of these oscillations as a weak anisotropy pattern in the image of the CMB.
- Statistical theory: all information encoded in the angular power spectrum of the image.

Density perturbations ($\Delta\rho/\rho$) were **oscillating** in the primeval plasma (as a result of the opposite effects of gravity and photon pressure).



Due to gravity,
$\Delta\rho/\rho$ increases,
and so does T

T is reduced enough
that gravity wins again

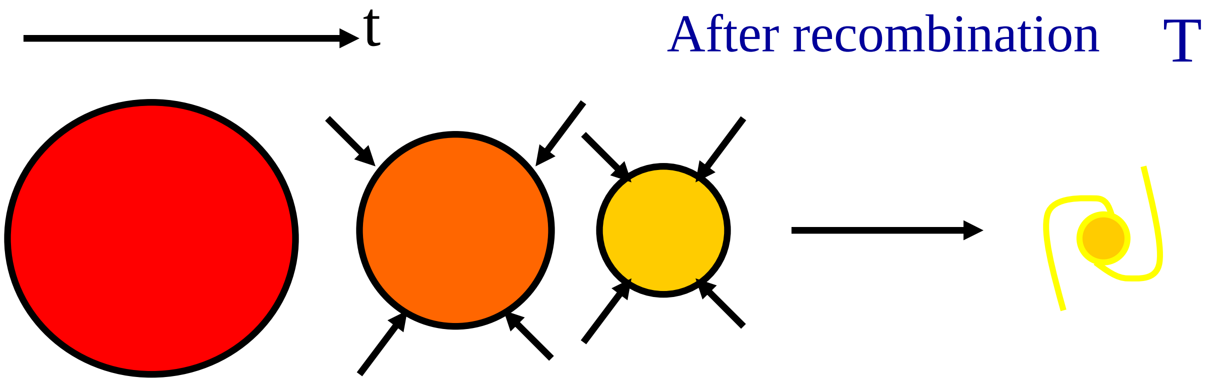
overdensity

t

Pressure of photons
increases, resisting to the
compression, and the
perturbation bounces back

Before recombination $T > 3000$ K

After recombination $T < 3000$ K

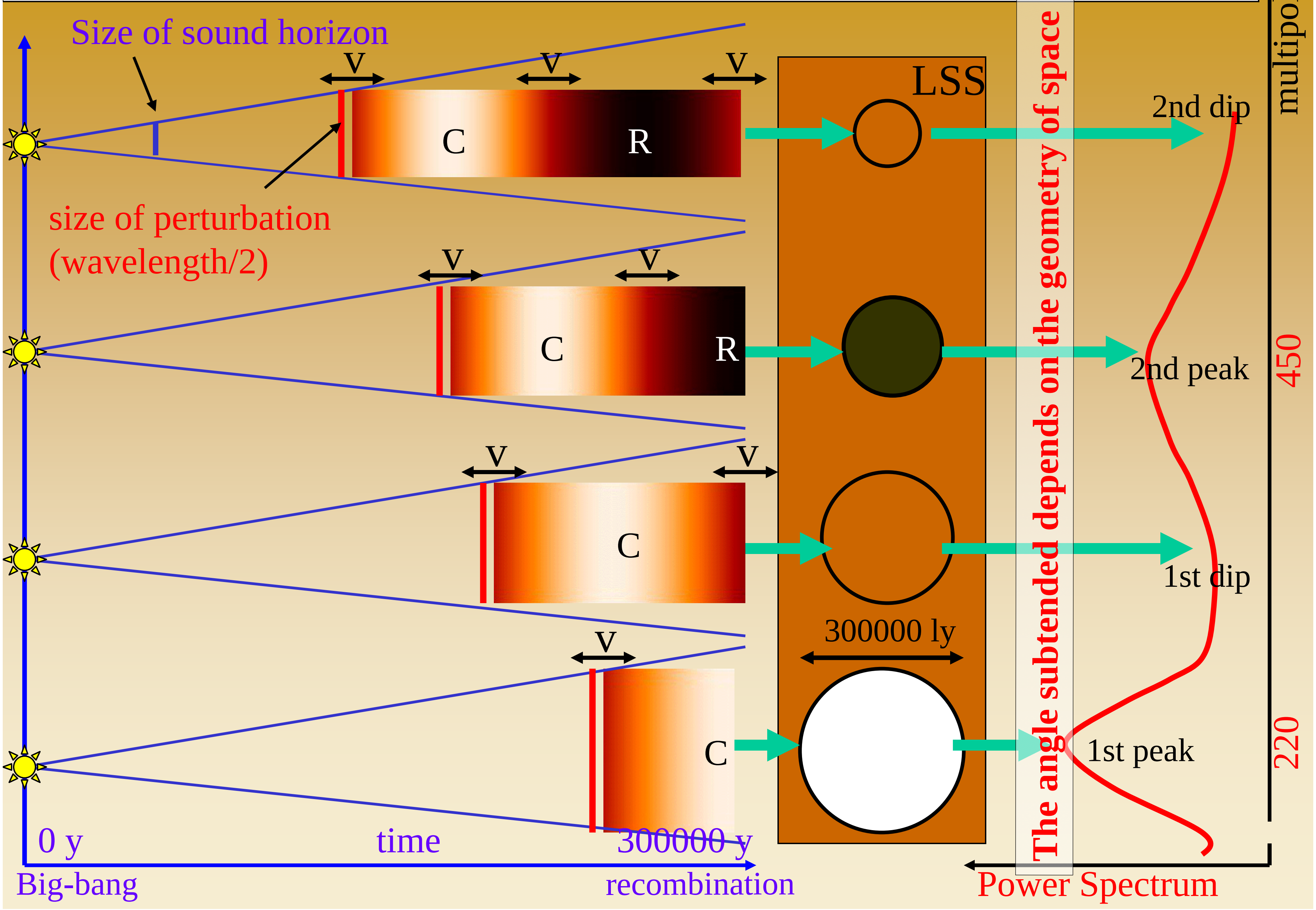


t

Here photons are not tightly
coupled to matter, and their
pressure is not effective.
Perturbations can grow and
form Galaxies.

After recombination, density perturbation can **grow** and create the hierarchy of structures we see in the nearby Universe.

In the primeval plasma, photons/baryons density perturbations start to oscillate only when the sound horizon becomes larger than their linear size . Small wavelength perturbations oscillate faster than large ones.



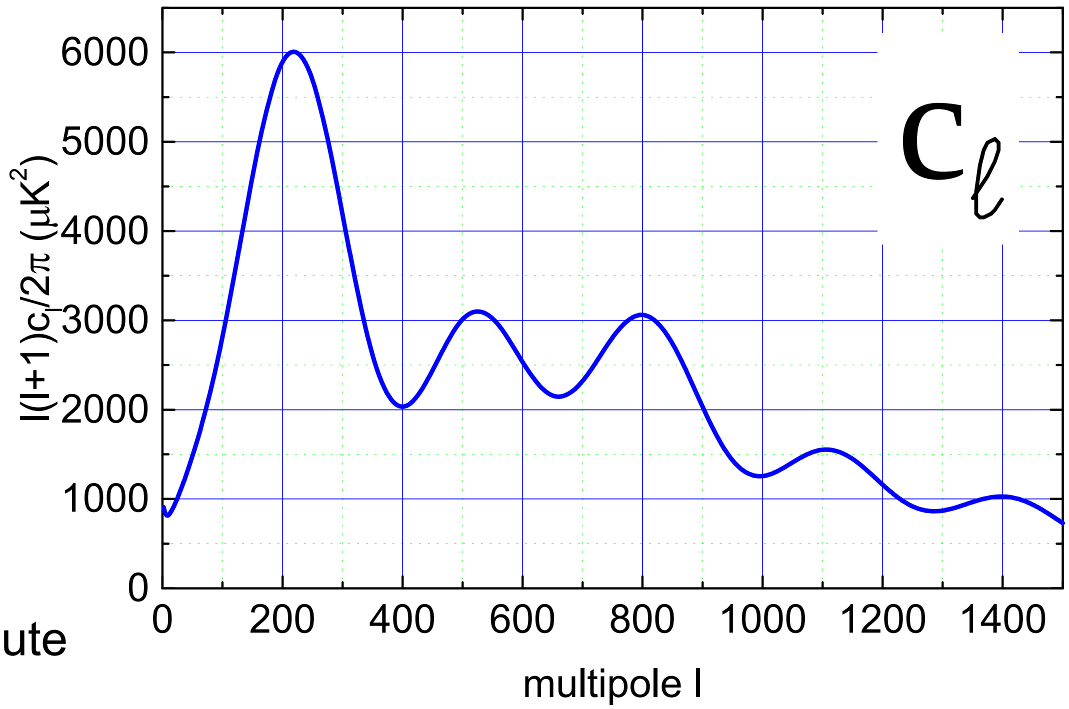
Expected power spectrum:

$$\Delta T(\theta,\varphi) = \sum_{\ell,m} a_{\ell m} Y_\ell^m(\theta,\varphi)$$

$$c_\ell = \left\langle a_{\ell m}^2 \right\rangle$$

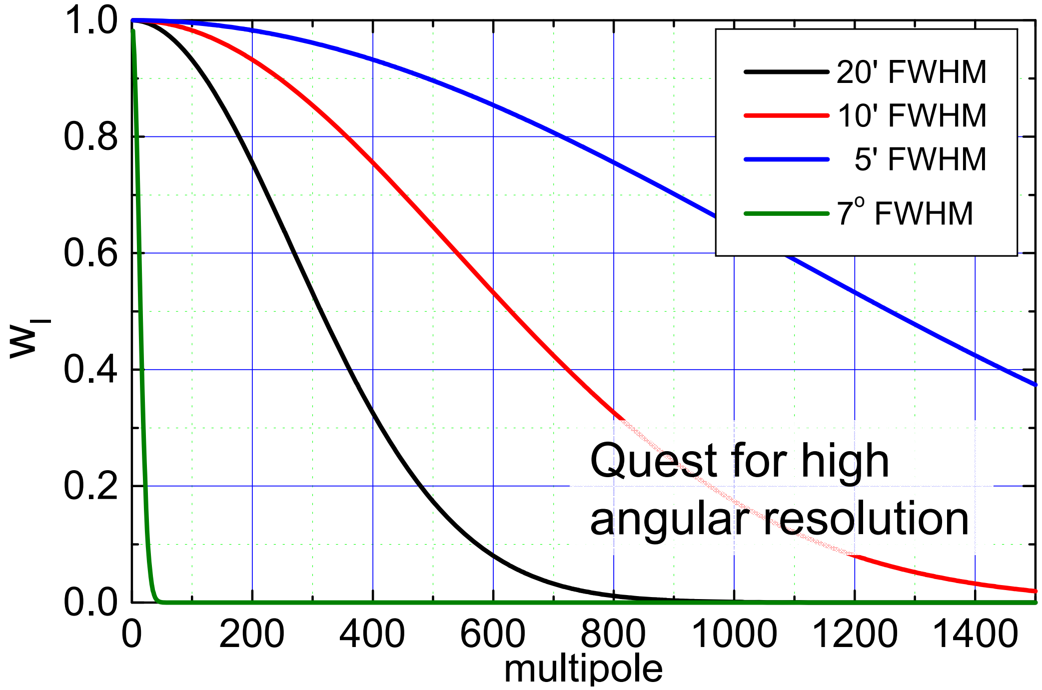
$$\left\langle \Delta T^2 \right\rangle = \frac{1}{4\pi} \sum_\ell (2\ell+1) c_\ell$$

See e.g. http://camb.info to compute c_ℓ for a given cosmological model

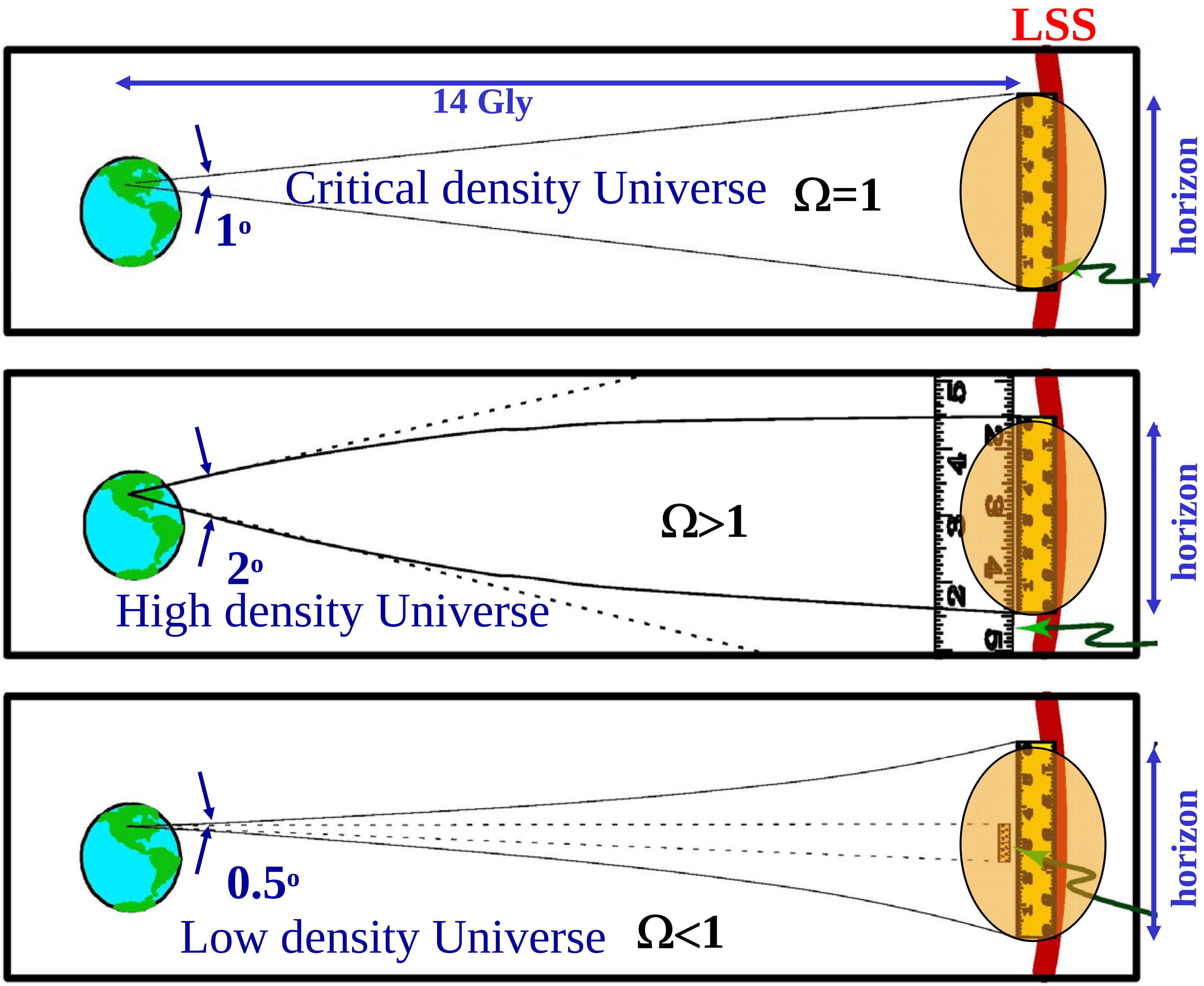


An instrument with finite angular resolution is not sensitive to the smallest scales (highest multipoles). For a gaussian beam with s.d. σ:

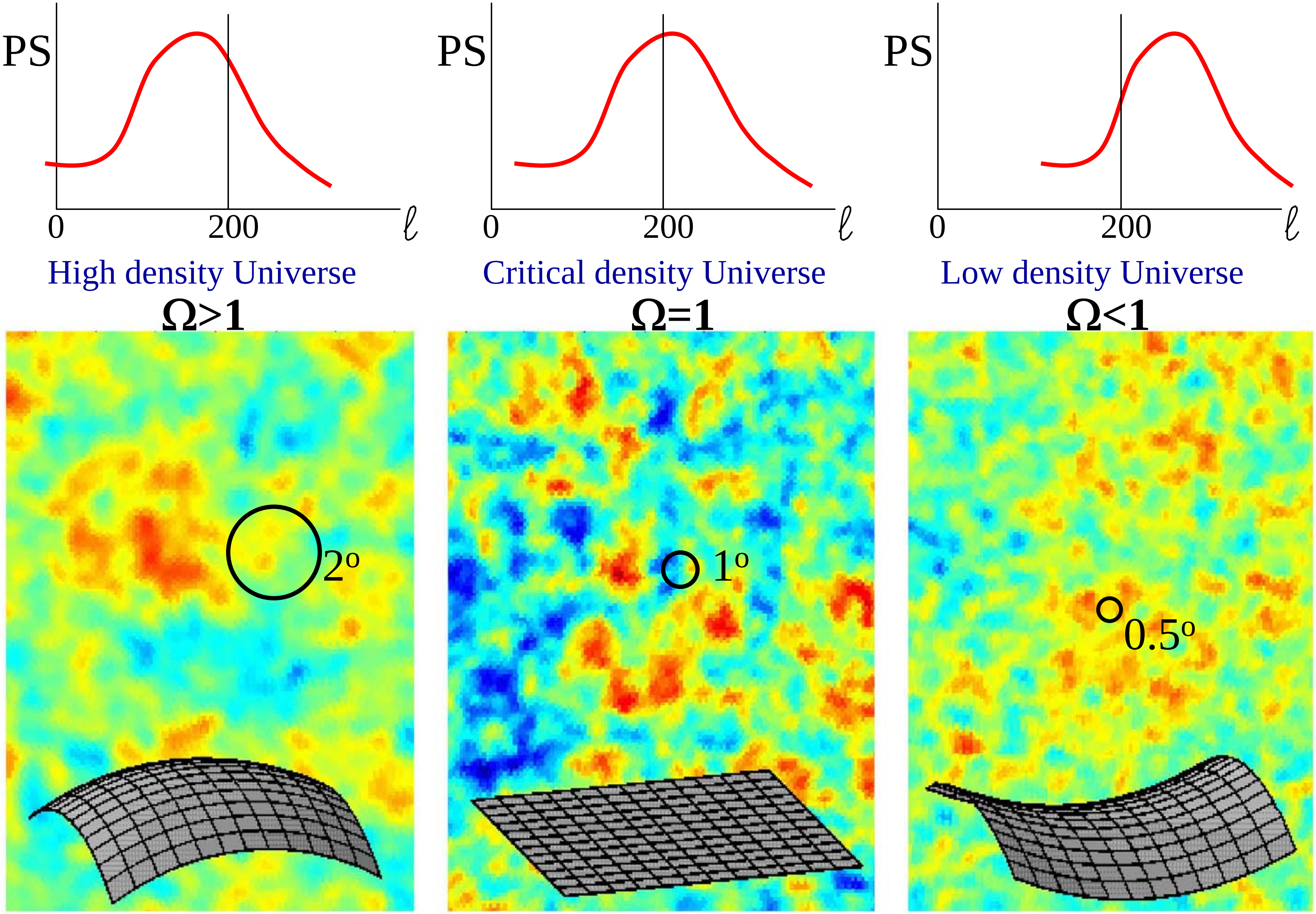
$$w_\ell^{LP} = e^{-\ell(\ell+1)\sigma^2}$$



Quest for high angular resolution



The image and PS are modified by the geometry of the universe



High density Universe **$\Omega > 1$**

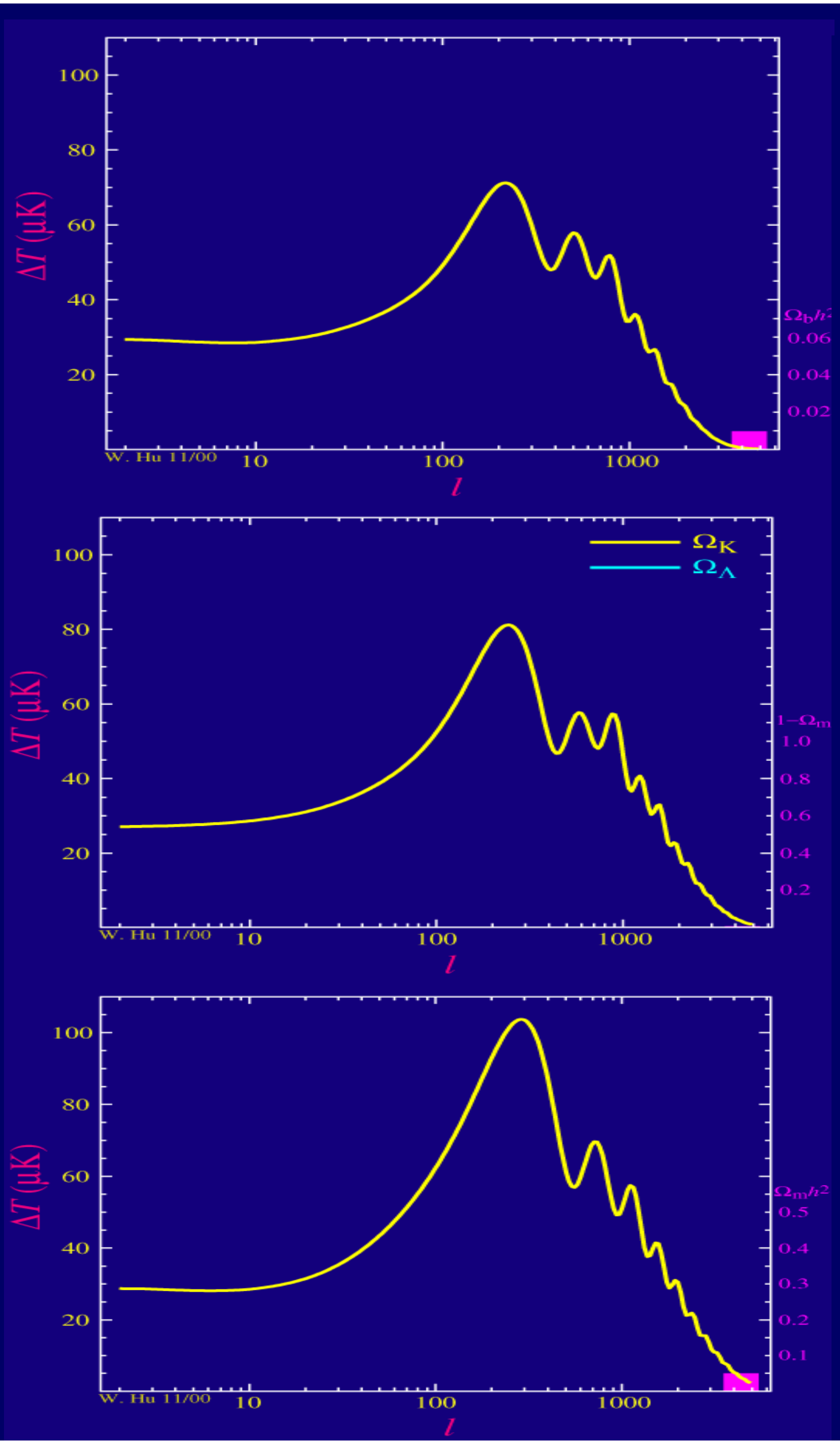
Critical density Universe **$\Omega = 1$**

Low density Universe **$\Omega < 1$**

The mass-energy density of the Universe can be measured in this way.

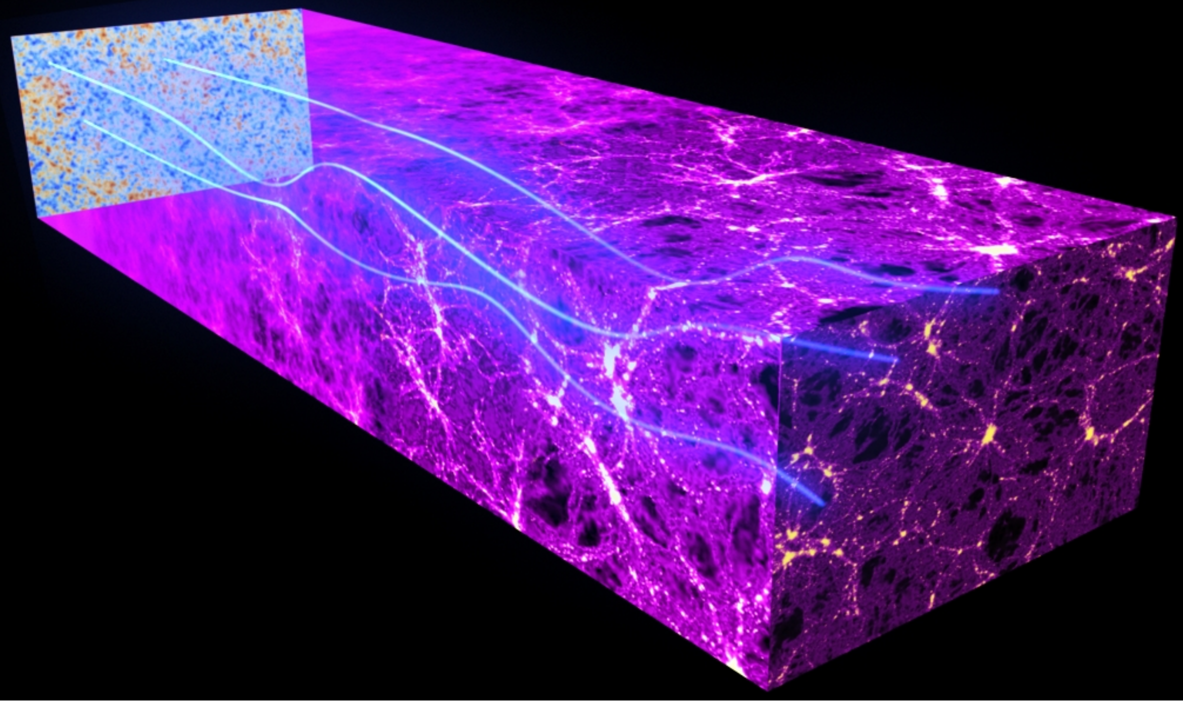
Composition

- The composition of the universe (baryons, dark matter, dark energy) affects the shape of the power spectrum.
- Accurate measurements of the power spectrum allow to constrain the energy densities of the different components of the universe.

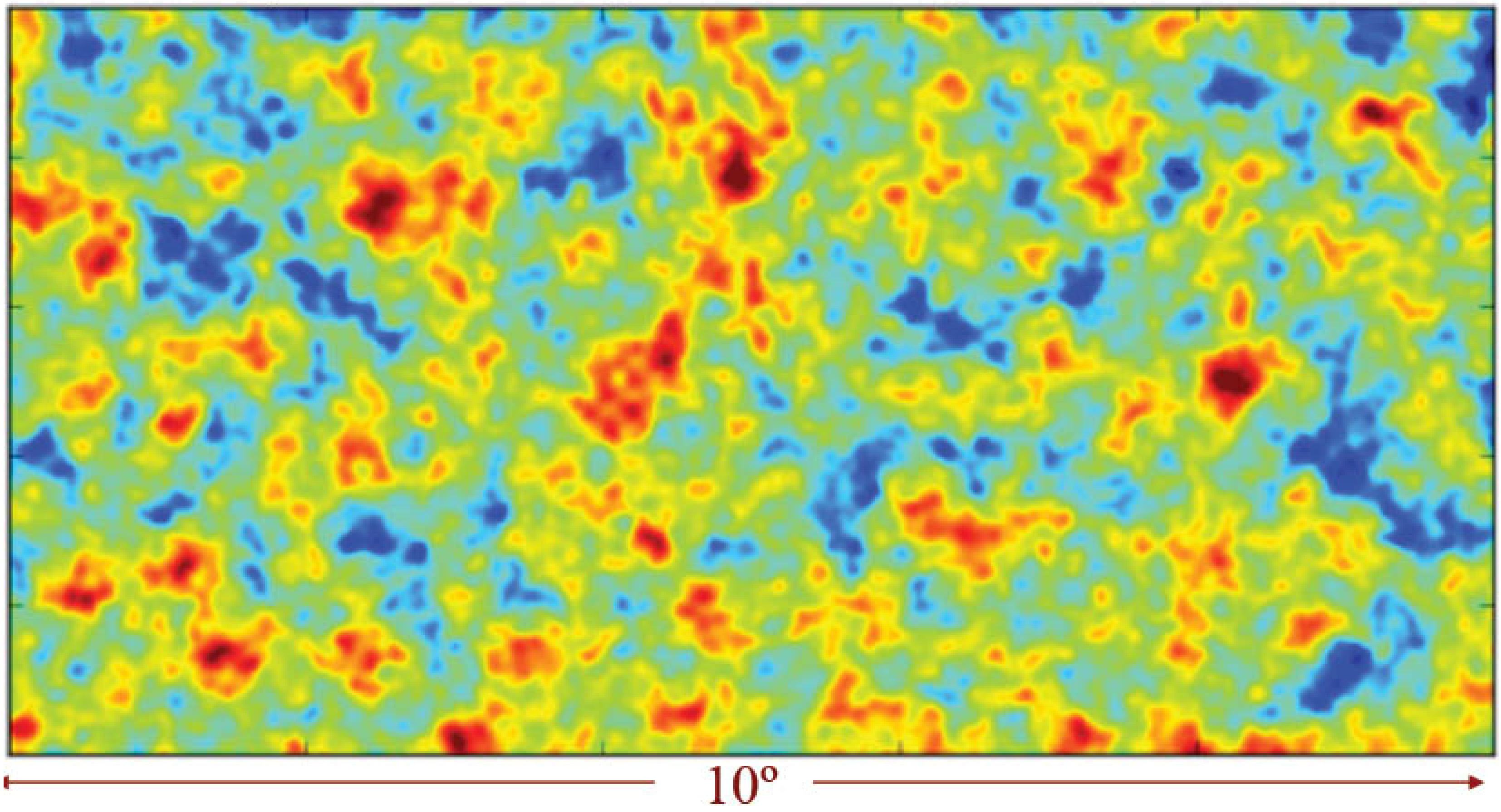


CMB anisotropy (lensing)

- Photons travelling in the universe for 13.7 Gly interact with massive structures, and are deflected (gravitational lensing)
- The result is a modified image of CMB anisotropy, which can be analyzed to study the distribution of mass (mainly dark matter) all the way to recombination.

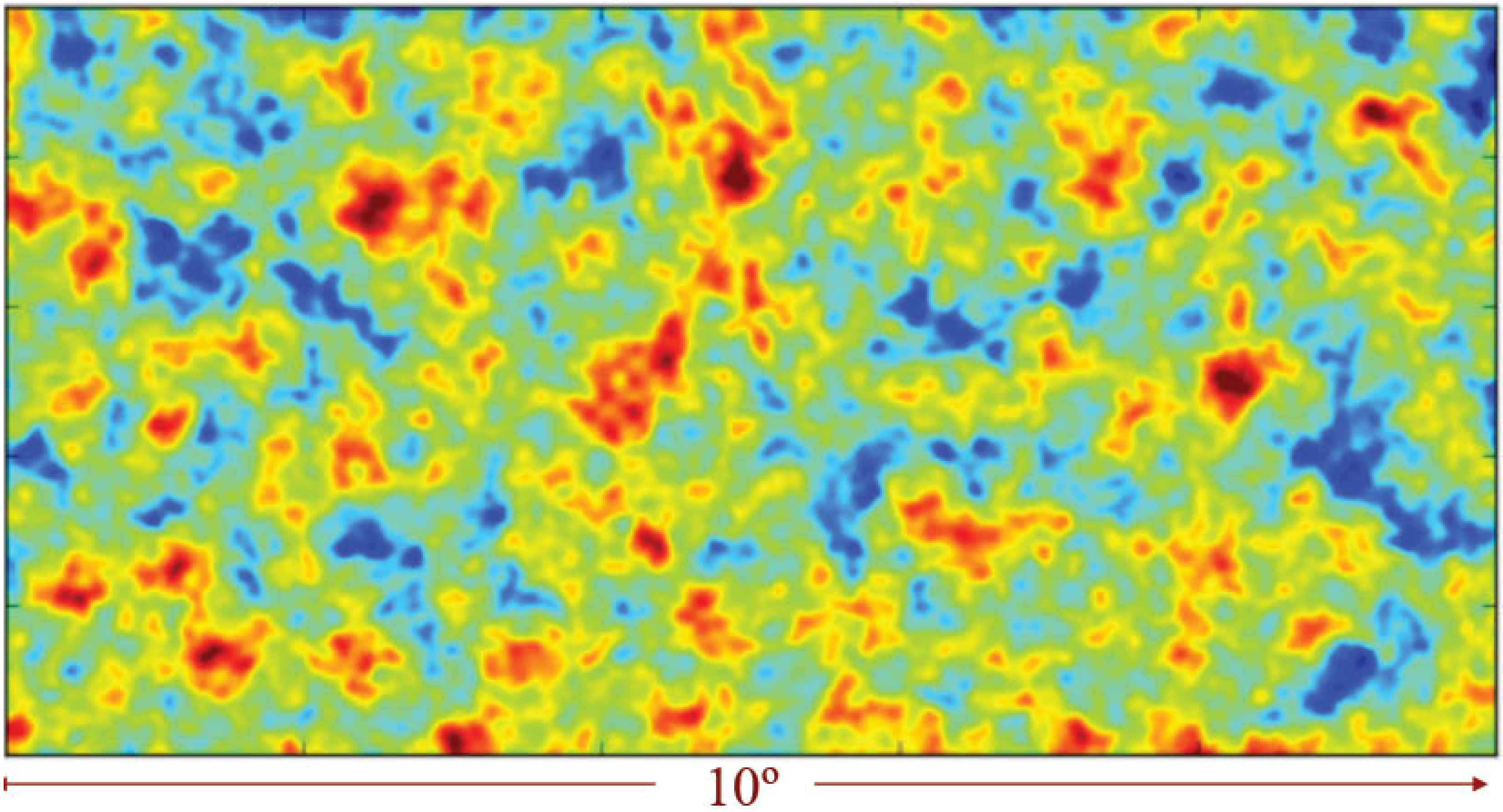


Typical deflection: 2.5’


intrinsic CMB anisotropy

Typical deflection: 2.5’

lensed CMB anisotropy



LSS and neutrino masses

- This lensing effect is due to the distribution of mass (mainly dark) at large scales.
- The formation of large scale structures in the universe depends on the presence and mass of free-streaming neutrinos.

Matter power spectrum

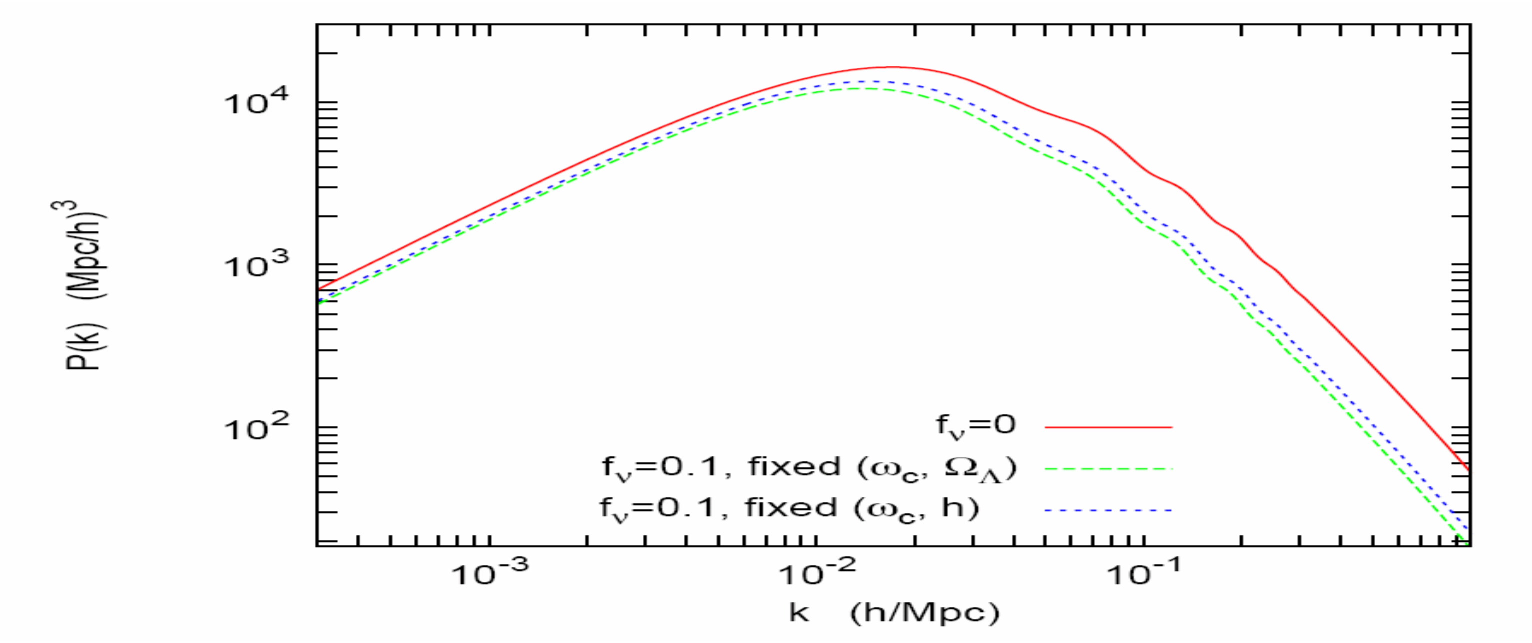
$$P_m(k,z) = \left\langle \left. \frac{\delta\rho}{\rho} \right|_{k,z}^{2} \right\rangle = Ak^n \cdot T^2(k,z)$$

Wavenumber (Mpc^{-1})

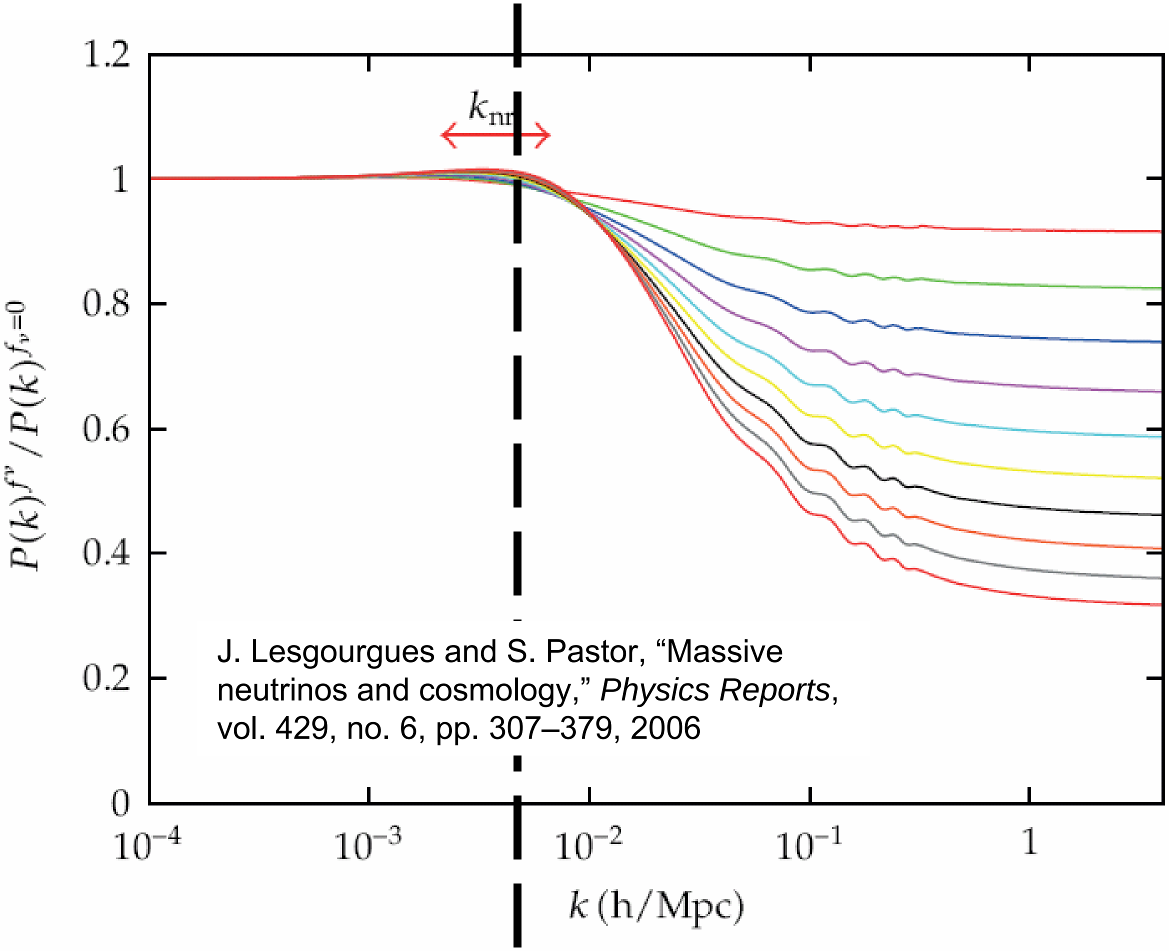
Redshift (epoch)

Primordial (inflation ?)

Transfer function describing the growth of density fluctuations



Effects on Matter power spectrum



J. Lesgourgues and S. Pastor, "Massive neutrinos and cosmology," *Physics Reports*, vol. 429, no. 6, pp. 307–379, 2006

$m_1=m_2=m_3$

m_i=0.046 eV

m_i=0.46 eV

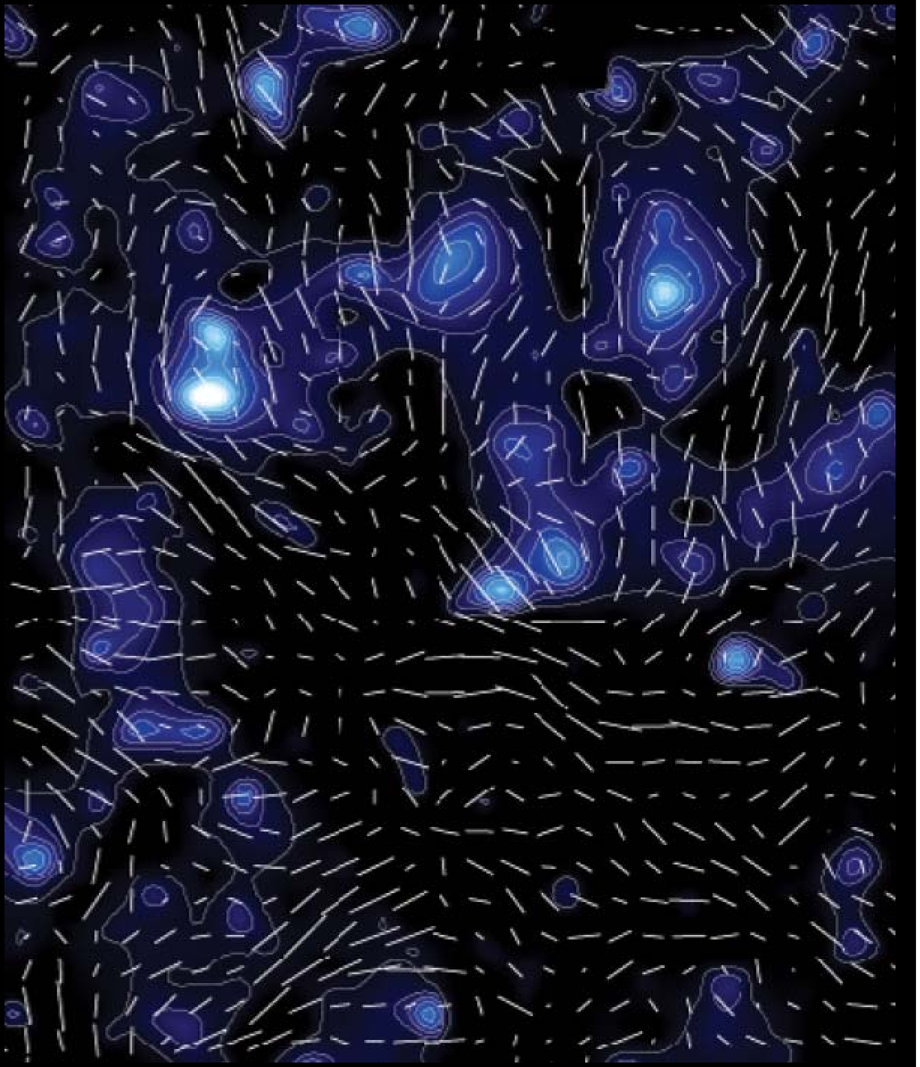
Large scales: effect of ν free-streaming negligible, ν act as CDM

Small scales: (ν cannot be confined within scales smaller than free-streaming length)

- Absence of ν perturbations
- Slower growth rate of CDM/Baryons perturbations

Galaxy lensing surveys

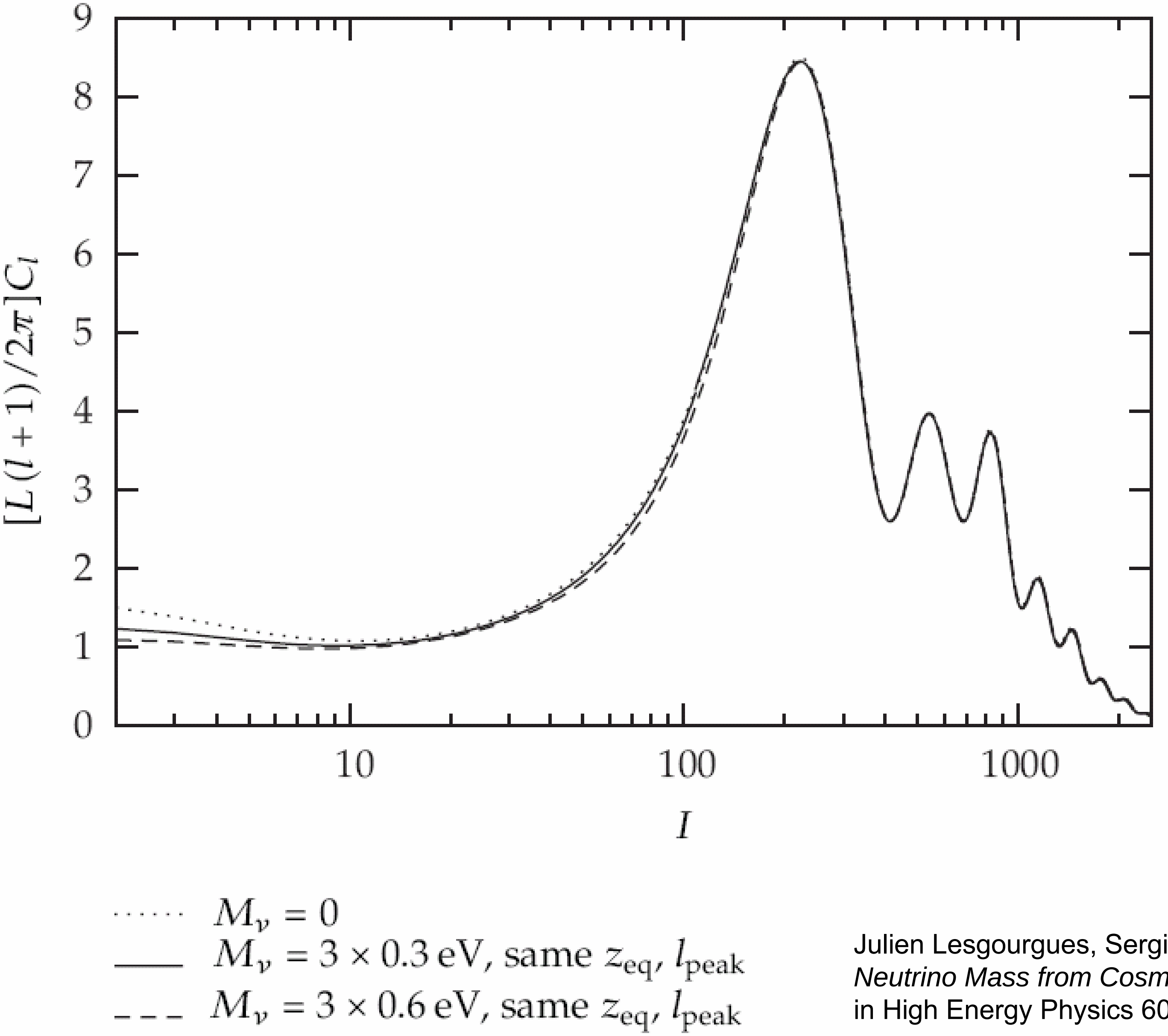
- Images of galaxies are distorted by weak gravitational lensing, due to the intervening total mass distribution between the sources and the observer
- Stretching the image in a direction and squeezing in the orthogonal direction (cosmic shear)
- Distortions coherent over size of density fluctuations, tend to align the major axis of galaxies over the same size.
- The lensing potential can be retrieved from the distortion map.
- Possible to recover the lensing potential in redshift bins



Dark matter distribution (color) inferred from shear field measurements (lines, from Massey et al. 2007). Each line is estimated averaging the shapes of about 200 galaxies present in the pixel .

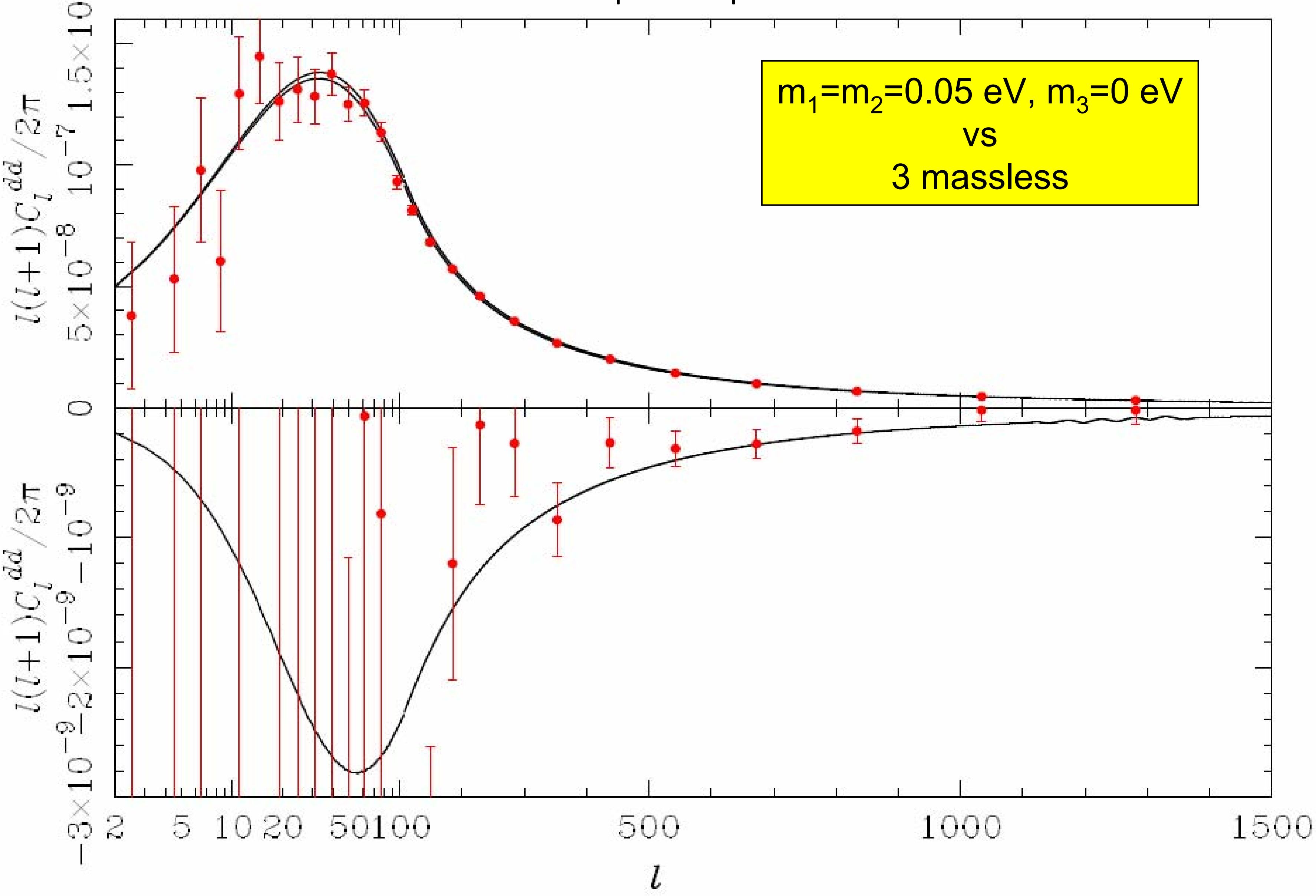
ν mass and the power spectrum of the CMB

- If M_n<1eV , massive neutrinos become non-relativistic after H recombination.
- The shape of the power spectrum of the CMB is mostly determined by physics before recombination (acoustic oscillations), so the effect of massive neutrinos on the CMB PS is small.
- However:
  - The presence of massive neutrinos modifies the evolution of the background universe. They count as radiation at matter/radiation equality, and as non-relativistic matter today. So their effect is either a change in the epoch of equality or a change in the Ω_m producing a change in the angular diameter distance of CMB. Both effect change the spectrum of the CMB. Small effects, and also degenerate with other parameter changes. To be used in combination with other observables. **BUT VERY STABLE !**
  - The fine structure of CMB anisotropy and polarization is affected by lensing, so is sensitive to the matter power spectrum, which in turn depends on n mass. **More powerful probes, BUT SUFFER THE SAME "ASTROPHYSICS" PROBLEMS OF MATTER PS**



Julien Lesgourgues, Sergio Pastor :
Neutrino Mass from Cosmology Advances
in High Energy Physics 608515 (2012)

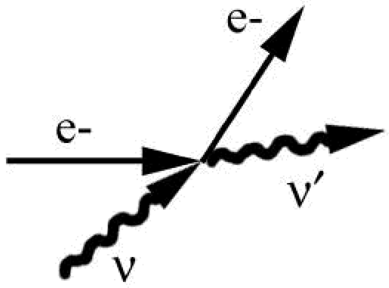
Deflection power spectrum

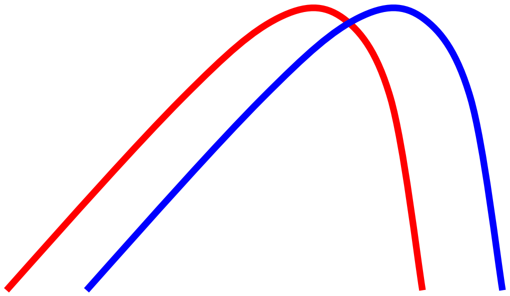


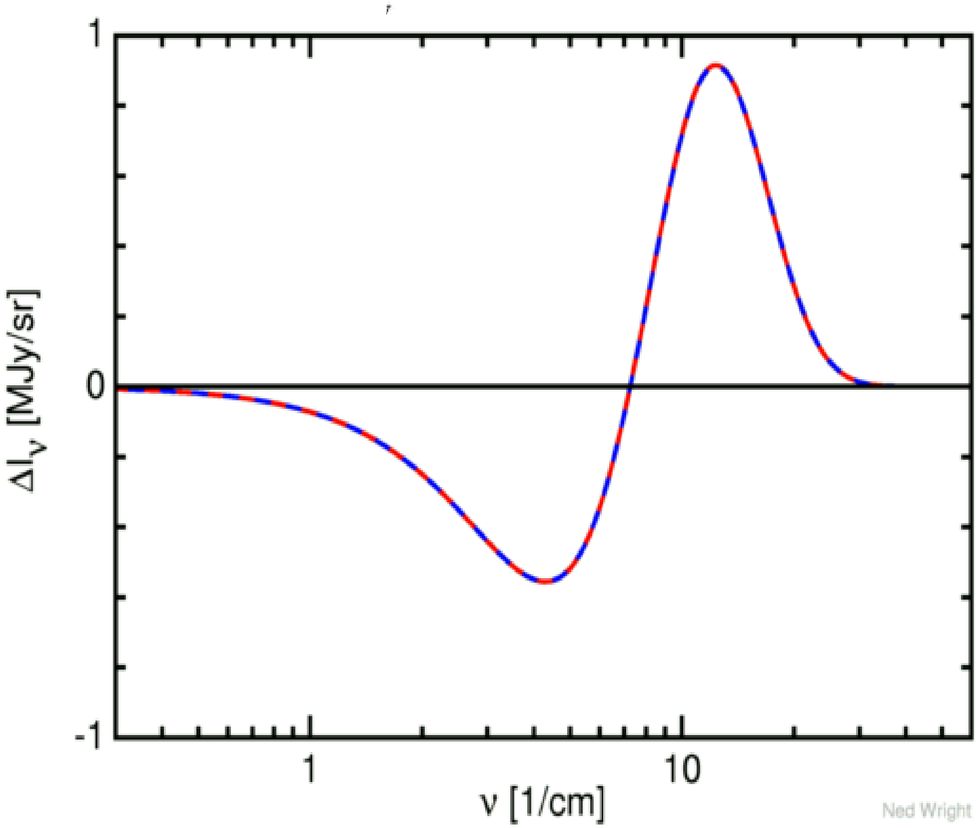
m_1=m_2=0.05 eV, m_3=0 eV
vs
3 massless

Sunyaev-Zeldovich effect

- CMB photons are inverse-compton scattered by the hot plasma in clusters of galaxies
- Being a scattering effect, does not depend on the distance of the cluster from us.
- The spectrum is shifted towards higher energies – very characteristic spectral feature.
- **Clusters can be observed against the bright background of the CMB, since they first emerge in the universe.**



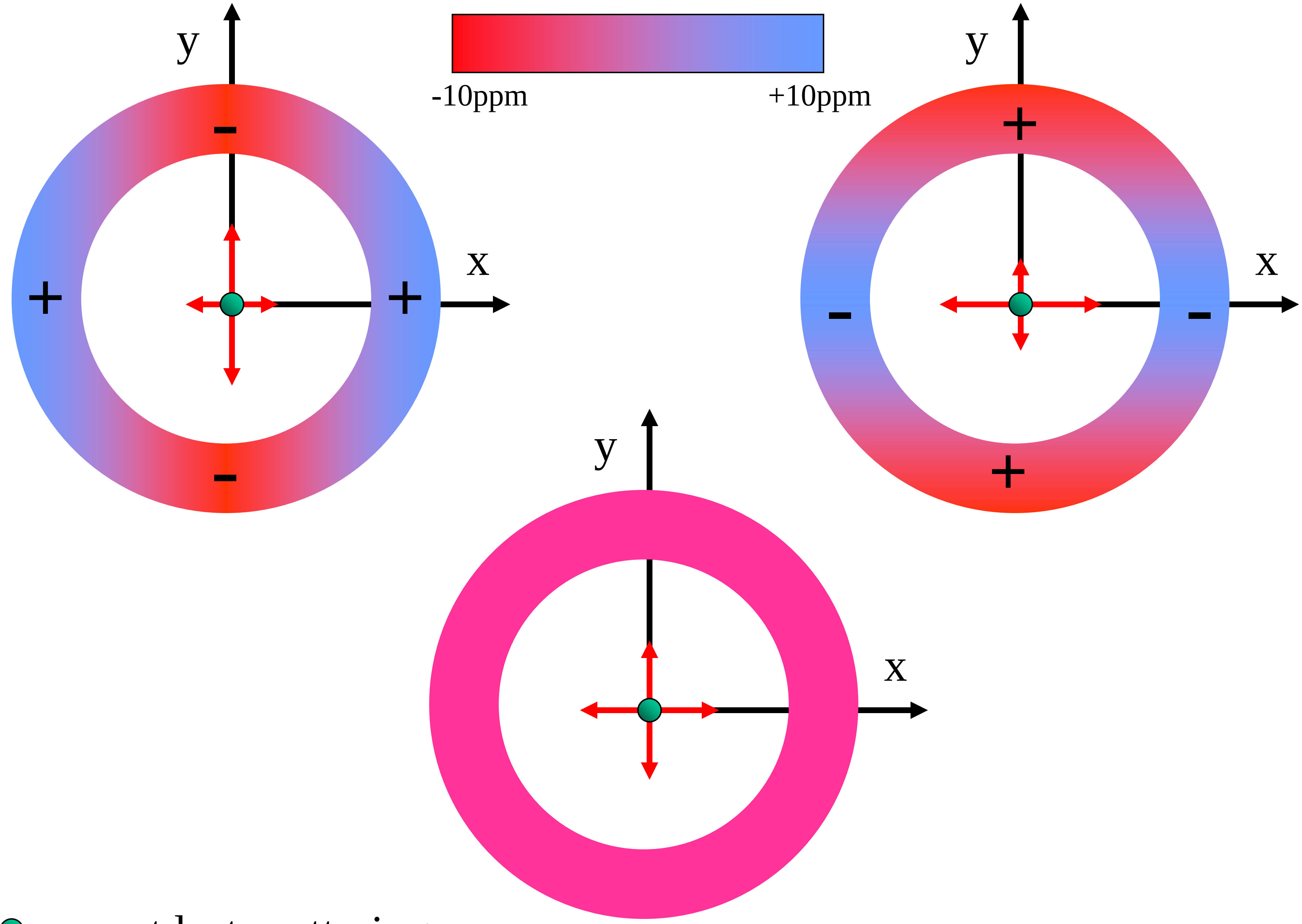




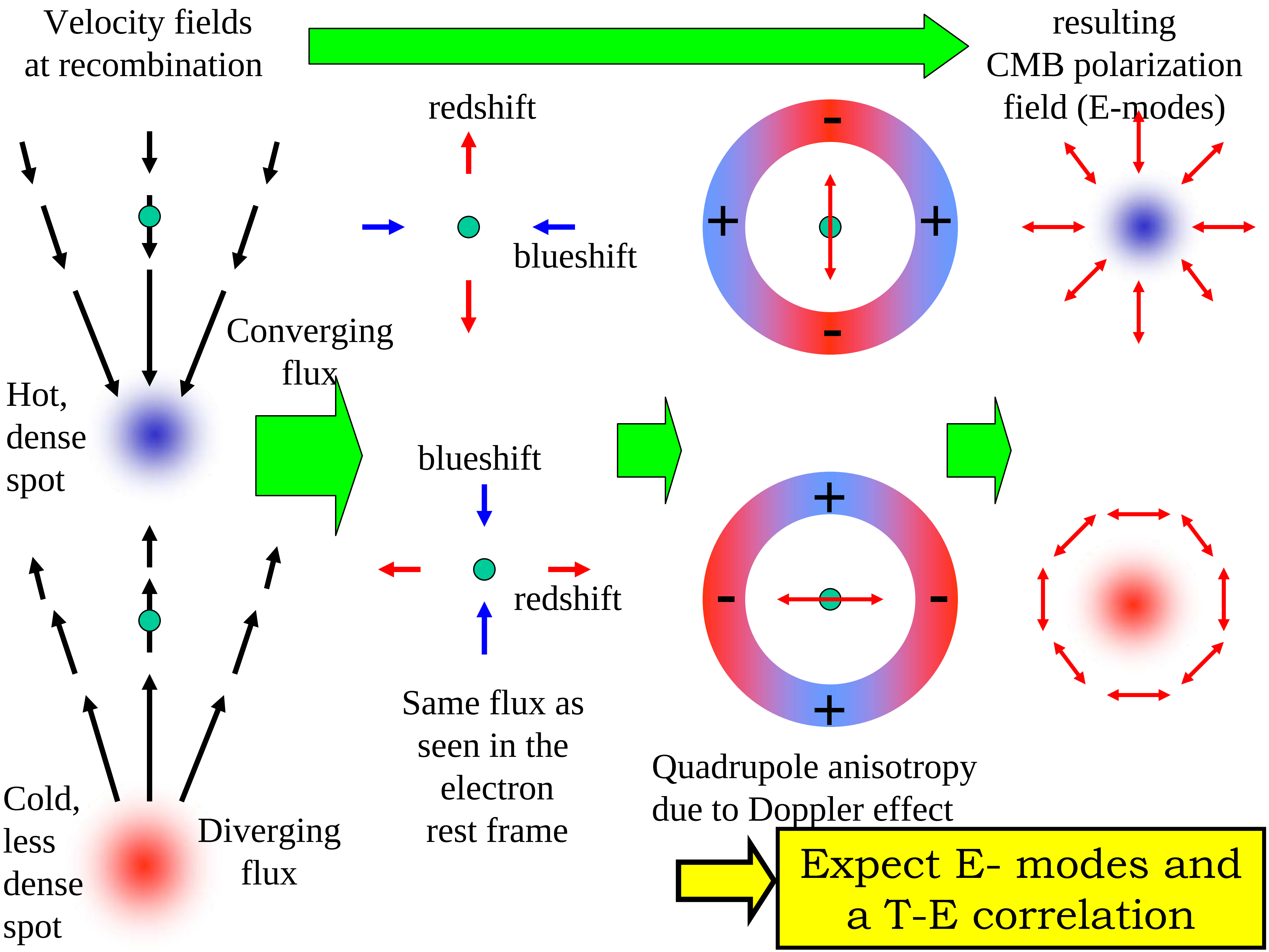
Ned Wright

CMB polarization (E)

- CMB photons are last scattered at recombination.
- It’s a Thomson scattering, and any quadrupole anisotropy in the incoming photons produces a degree of linear polarization in the scattered photons.
- Density perturbation produce a small degree of linear polarization (E-modes)



● = e$^-$ at last scattering



Velocity fields at recombination

resulting CMB polarization field (E-modes)

Hot, dense spot

Converging flux

redshift

blueshift

Cold, less dense spot

Diverging flux

blueshift

redshift

Same flux as seen in the electron rest frame

Quadrupole anisotropy due to Doppler effect

Expect E- modes and a T-E correlation

- E-modes are irrotational
- E modes are related to velocities, while T is related mainly to density
- We expect a power spectrum of the E-modes, <EE>, with maxima and mimina in quadrature with the anisotropy power spectrum <TT>.

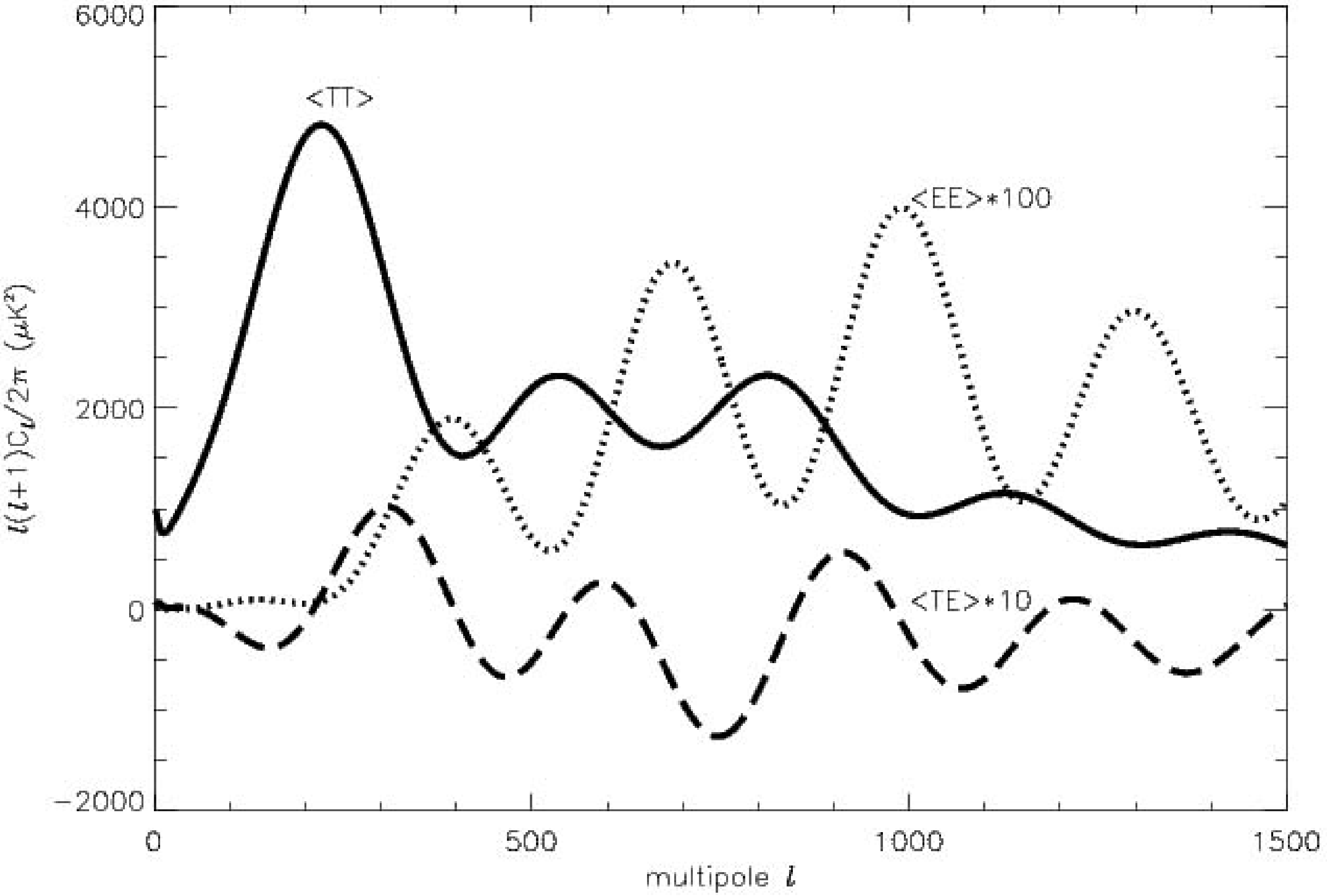


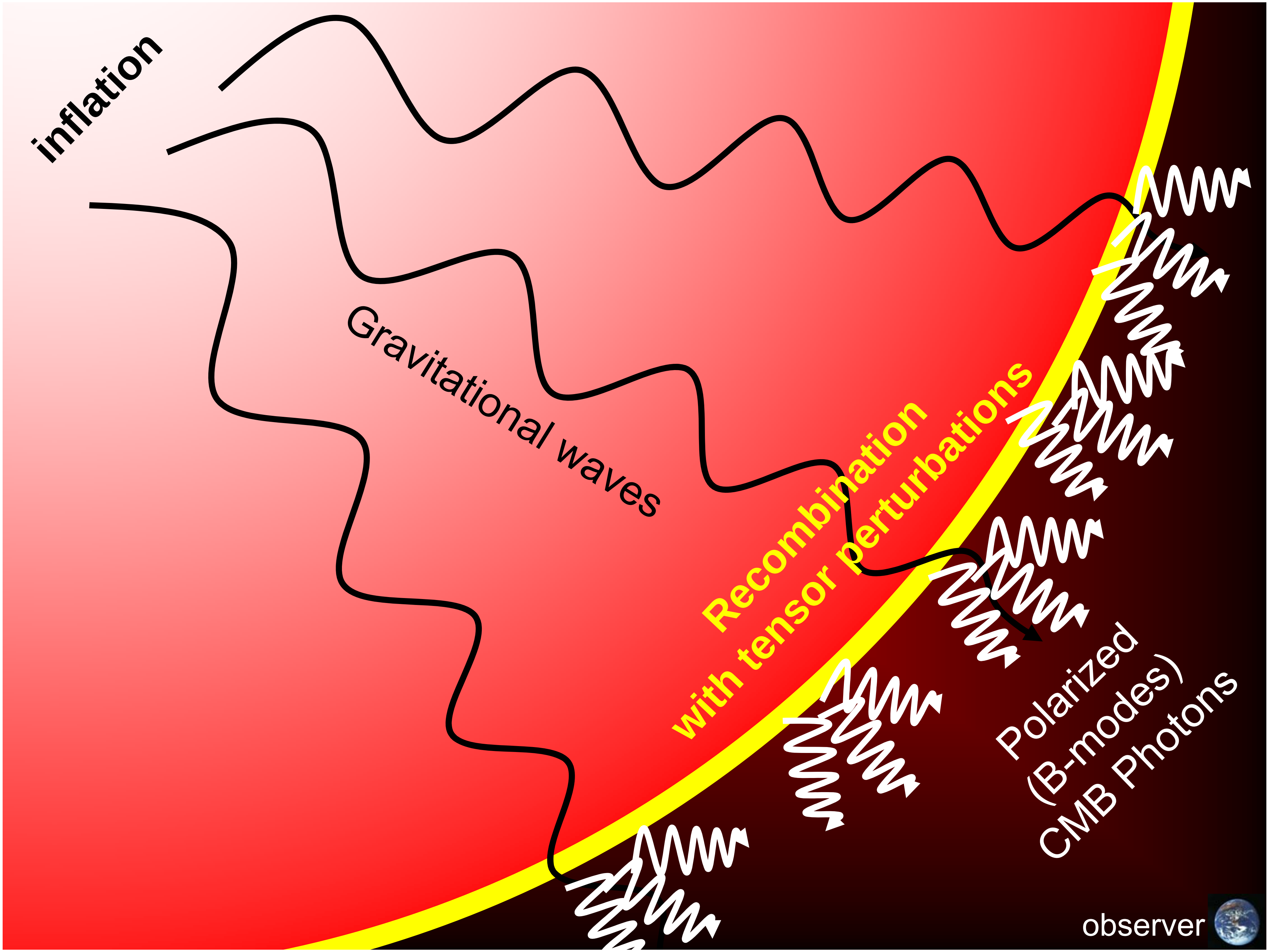
Figure 1.7: Estimated power spectra for the cosmological parameters: $\Omega_b = 0.05$, $\Omega_{cdm} = 0.3$, $\Omega_\Lambda = 0.65$, $\Omega_\nu = 0$, $H_0 = 65$ km/s/Mpc, $\tau = 0.17$. The temperature power spectrum, $\langle TT \rangle = C_\ell^T$, the E-modes power spectrum $\langle EE \rangle = C_\ell^E$ multiplied by a factor 100 to make it visible and the cross power spectrum between temperature and polarization, $\langle TE \rangle = C_\ell^{TE}$ multiplied by a factor 10. The spectra are computed using the publicly available code CMBFAST (http://www.cmbfast.org),

CMB polarization (B)

- CMB photons are last scattered at recombination.
- It’s a Thomson scattering, and any quadrupole anisotropy in the incoming photons produces a degree of linear polarization in the scattered photons.
- Tensor perturbations (gravitational waves) produce a small degree of linear polarization with curl properties (B-modes)
- Also, lensing of E-modes does the same at smaller scales

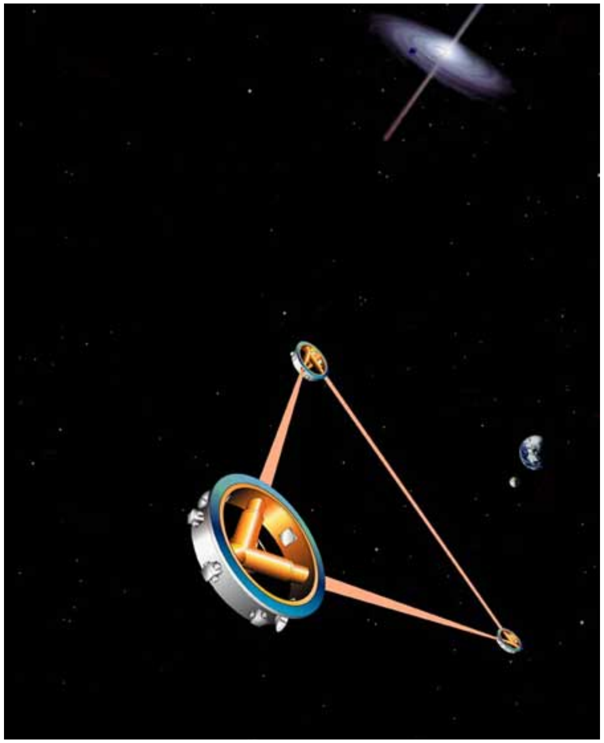
If inflation really happened...

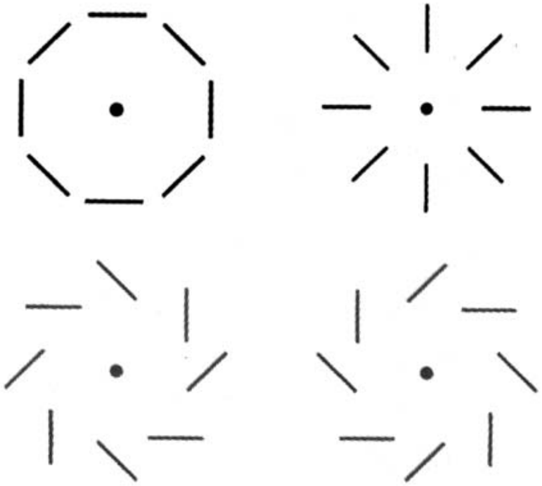
- It stretched geometry of space to nearly Euclidean ← OK
- It produced a nearly scale invariant spectrum of density fluctuations ← OK
- It produced a stochastic background of gravitational waves. ← ?


inflation
Gravitational waves
Recombination
with tensor perturbations
Polarized
(B-modes)
CMB Photons
observer

Quadrupole from P.G.W.

- If inflation really happened:
  - ✓ It stretched geometry of space to nearly Euclidean
  - ✓ It produced a nearly scale invariant spectrum of gaussian density fluctuations
  - ✓ It produced a stochastic background of gravitational waves: Primordial G.W. The background is so faint that even LISA will not be able to measure it.
- Tensor perturbations also produce quadrupole anisotropy. They generate irrotational (E-modes) **and rotational (B-modes) components** in the CMB polarization field.
- Since B-modes are not produced by scalar fluctuations, they represent a signature of inflation.





B-modes from P.G.W.

- The amplitude of this effect is very small, but depends on the Energy scale of inflation. In fact the amplitude of tensor modes normalized to the scalar ones is:

$$\left(\frac{T}{S}\right)^{1/4} \equiv \left(\frac{C_2^{GW}}{C_2^{Scalar}}\right)^{1/4} \cong \frac{V^{1/4}}{3.7\times 10^{16}\,\mathrm{GeV}}$$

← Inflation potential

- and

$$\sqrt{\frac{\ell(\ell+1)}{2\pi}c^B_{\ell\max}} \cong 0.1\mu K\left[\frac{V^{1/4}}{2\times 10^{16}\,\mathrm{GeV}}\right]$$

- There are theoretical arguments to expect that the energy scale of inflation is close to the scale of GUT i.e. around 10^{16} GeV.
- The current upper limit on anisotropy at large scales gives T/S<0.5 (at 2σ)
- A competing effect is lensing of E-modes, which is important at large multipoles.

E-modes & B-modes

Spin-2 quantity Spin-2 basis

$$(Q \pm iU)(\vec{n}) = \sum_{\ell,m} \left(a_{\ell m}^{E} \pm i a_{\ell m}^{B} \right) {}_{\pm 2}Y_{\ell m}(\vec{n})$$

- From the measurements of the Stokes Parameters ***Q*** and ***U*** of the linear polarization field we can recover both irrotational and rotational a_{lm} by means of modified Legendre transforms:

E-modes produced by scalar and tensor perturbations

$$a_{\ell m}^{E} = \frac{1}{2} \int d\Omega W(\vec{n}) \left[(Q + iU)(\vec{n})\, {}_{+2}Y_{\ell m}(\vec{n}) + (Q - iU)(\vec{n})\, {}_{-2}Y_{\ell m}(\vec{n}) \right]$$

B-modes produced **only** by tensor perturbations

$$a_{\ell m}^{B} = \frac{1}{2i} \int d\Omega W(\vec{n}) \left[(Q + iU)(\vec{n})\, {}_{+2}Y_{\ell m}(\vec{n}) - (Q - iU)(\vec{n})\, {}_{-2}Y_{\ell m}(\vec{n}) \right]$$

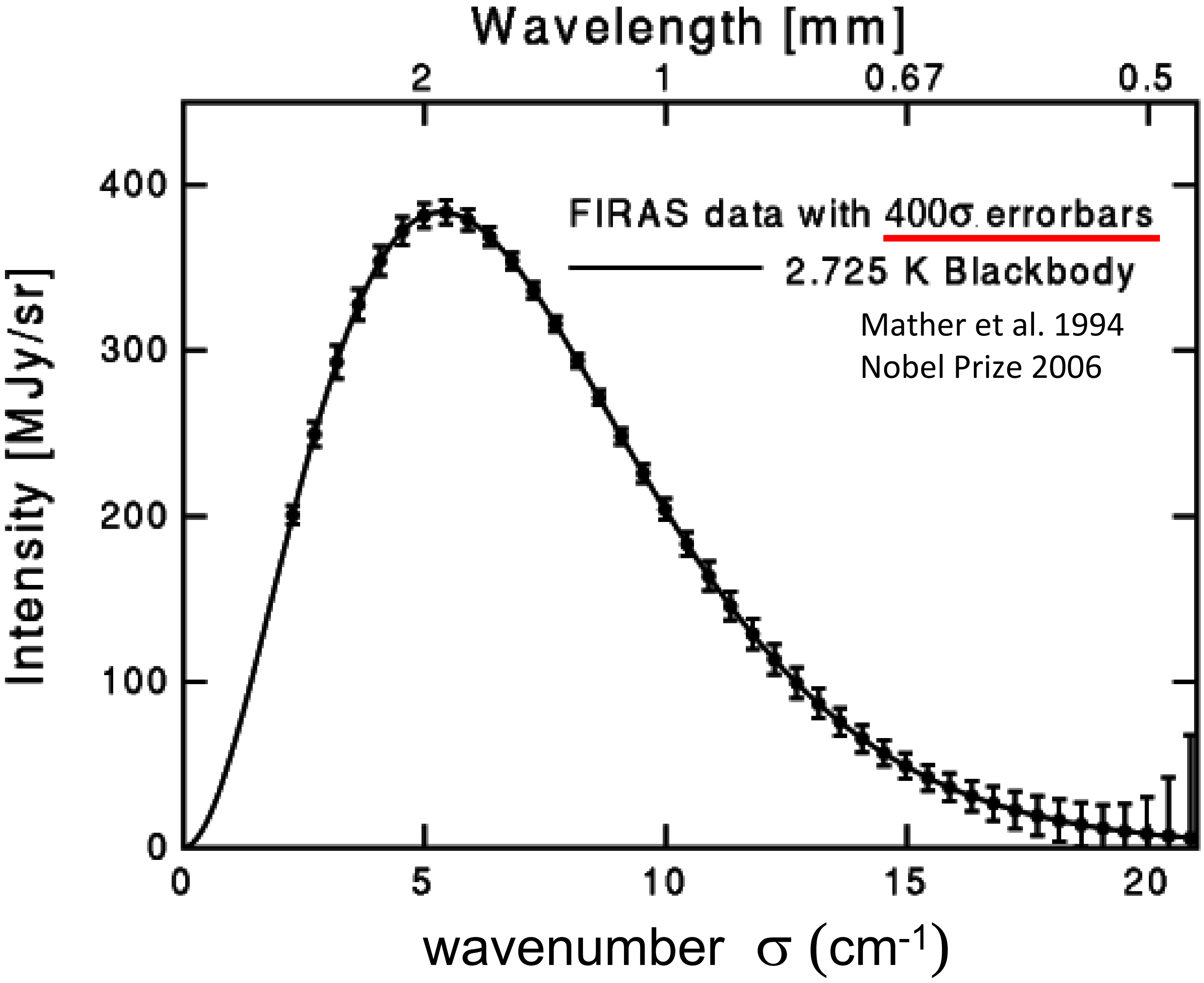
The signal is extremely weak

- Nobody really knows how to detect this.
  - Pathfinder experiments are needed
- Whatever smart, ambitious experiment we design to detect the B-modes:
  - It needs to be extremely sensitive
  - It needs an extremely careful control of systematic effects
  - It needs careful control of foregrounds
  - It will need independent experiments with orthogonal systematics.
- There is still a long way to go: ...

Most of this has been **measured** very successfully, and used to constrain cosmology.

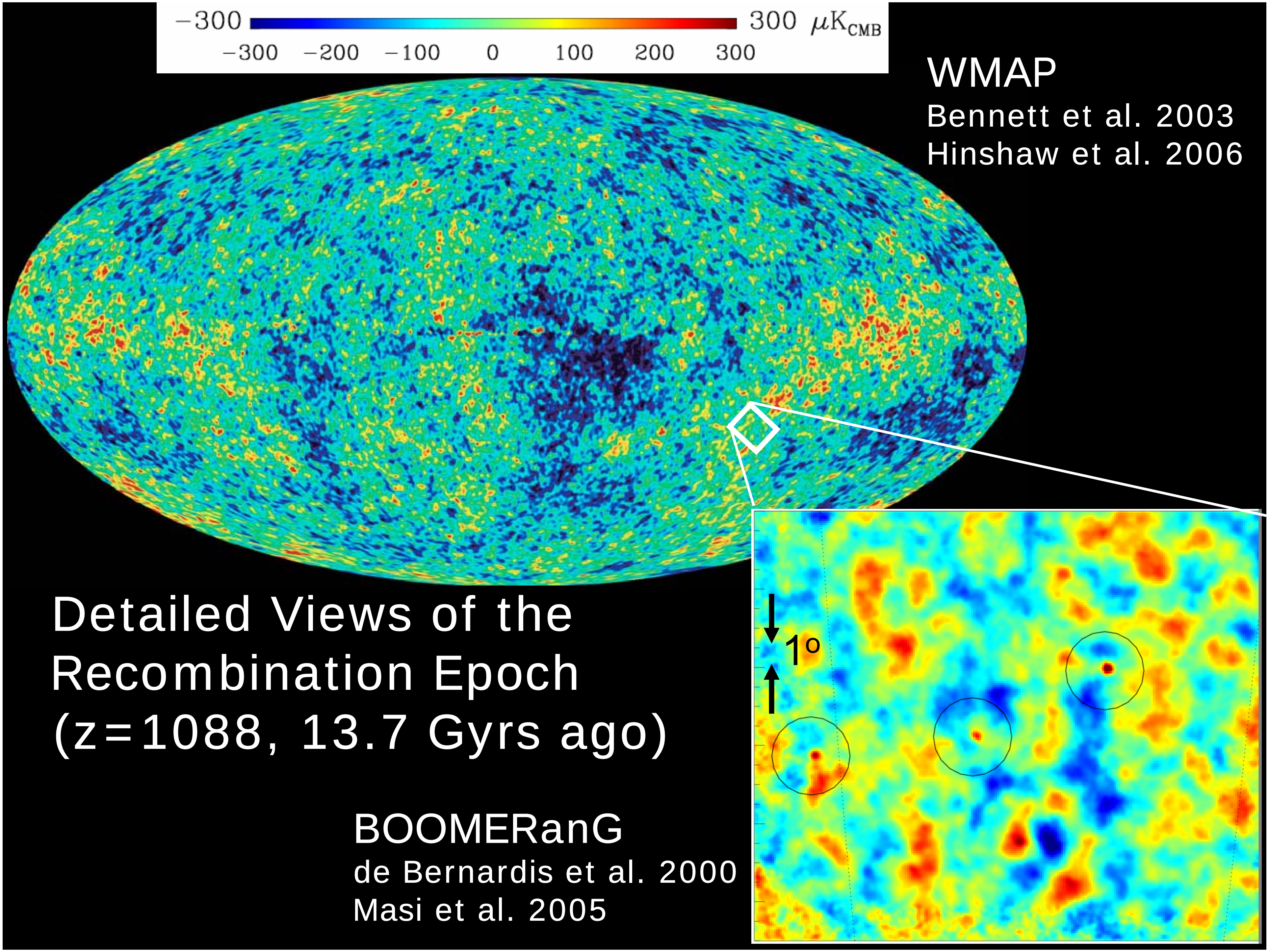
- Spectrum
- Intrinsic anisotropy (power spectrum)
- Lensing
- E-modes polarization
- SZ effect
- B-modes polarization

The spectrum: a proof of the primeval fireball



Mather et al. 1994
Nobel Prize 2006

Detailed Views of the Recombination Epoch (z=1088, 13.7 Gyrs ago)

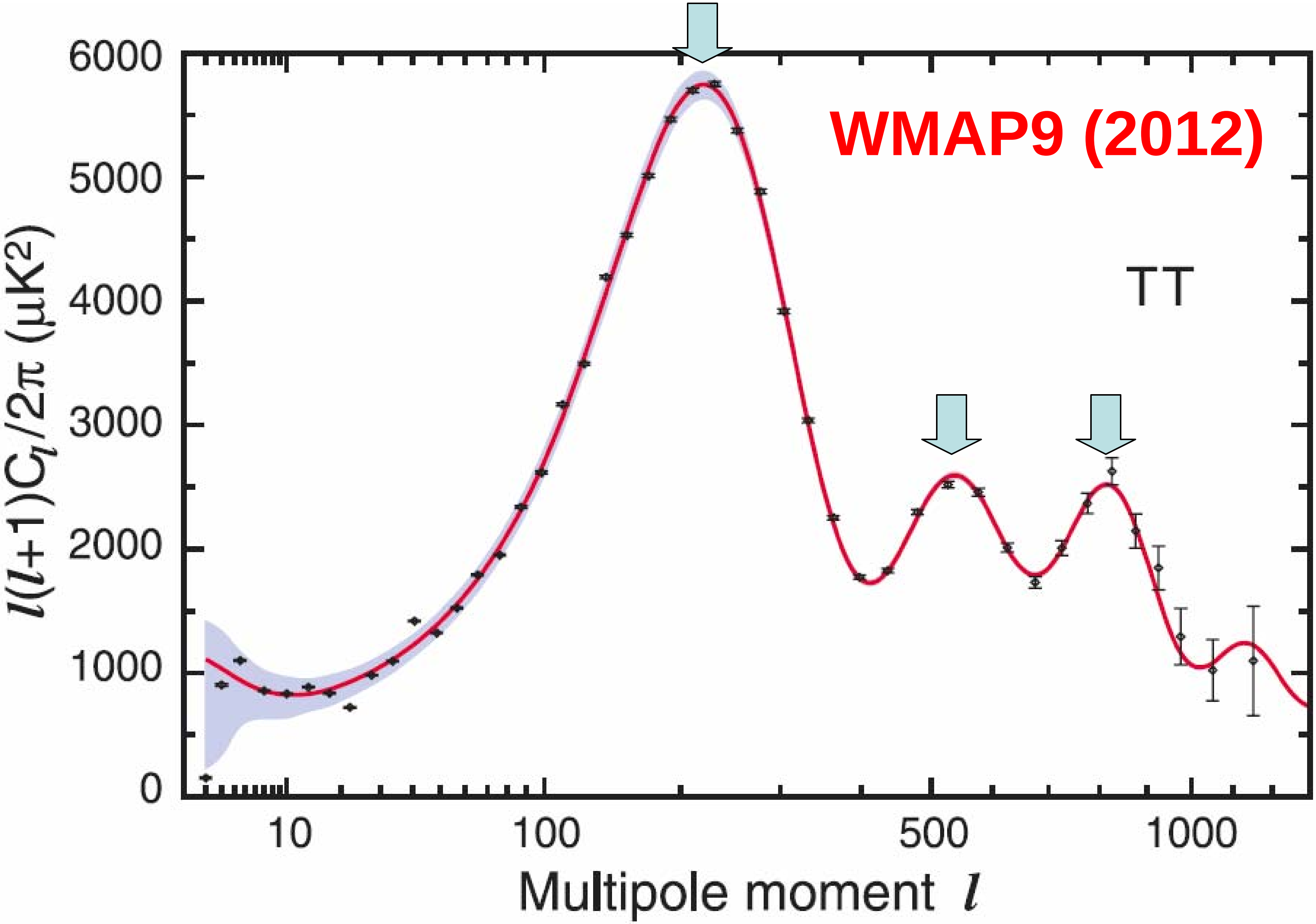


WMAP

Bennett et al. 2003
Hinshaw et al. 2006

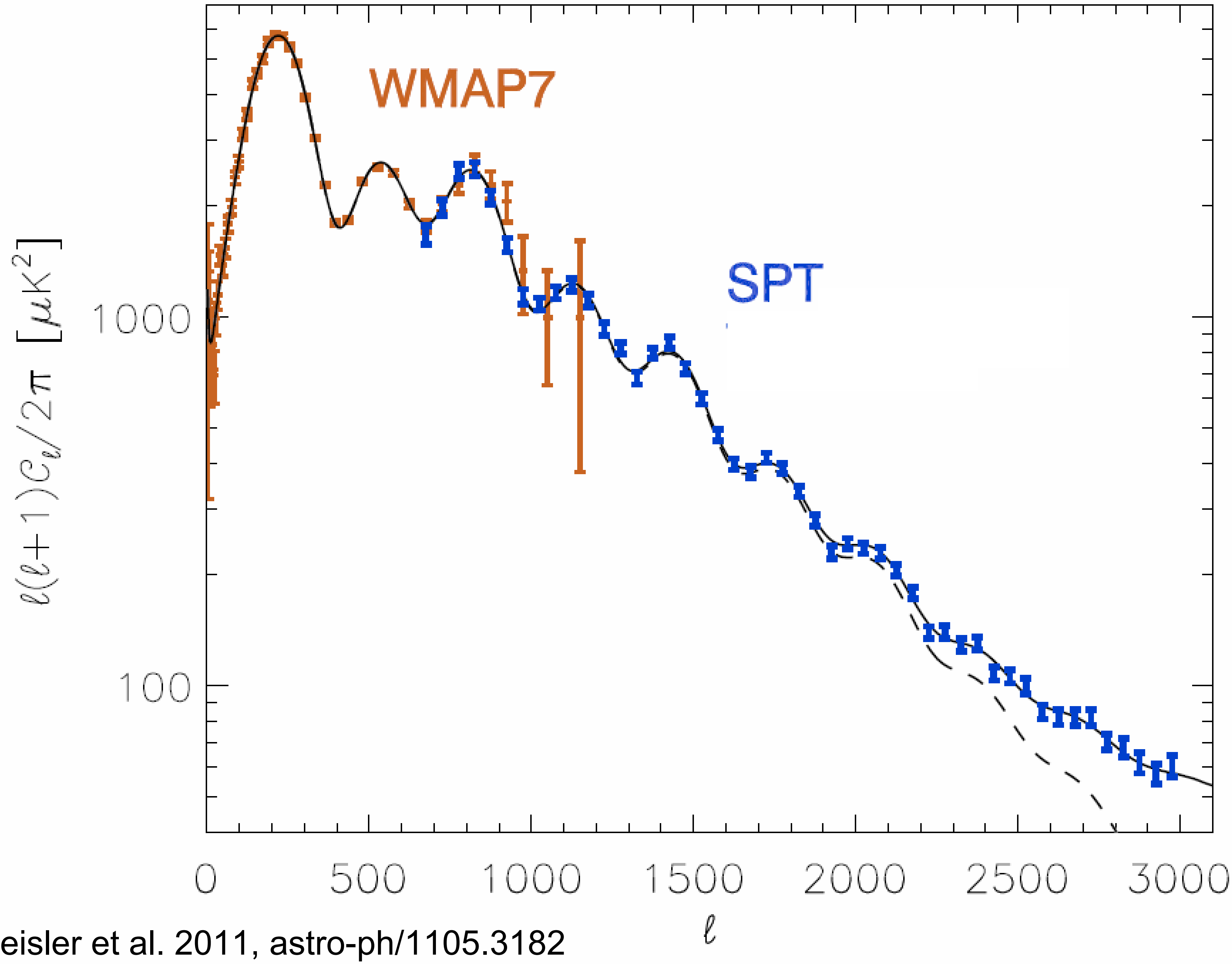
BOOMERanG

de Bernardis et al. 2000
Masi et al. 2005



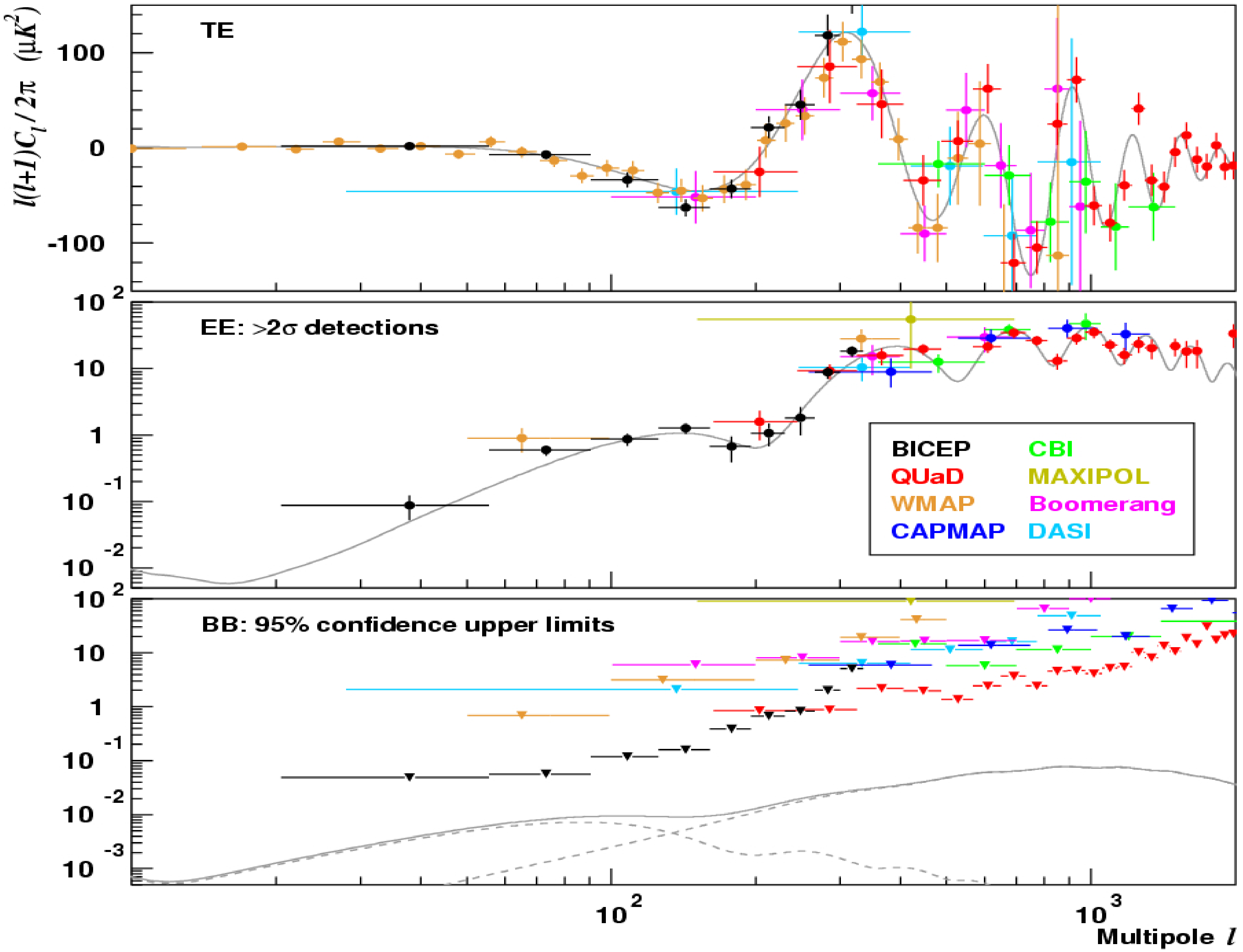
WMAP9 (2012)

TT
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
$l(l+1)C_l/2\pi$ (μK^2)
Multipole moment l



Keisler et al. 2011, astro-ph/1105.3182

CMB Polarization Measurements

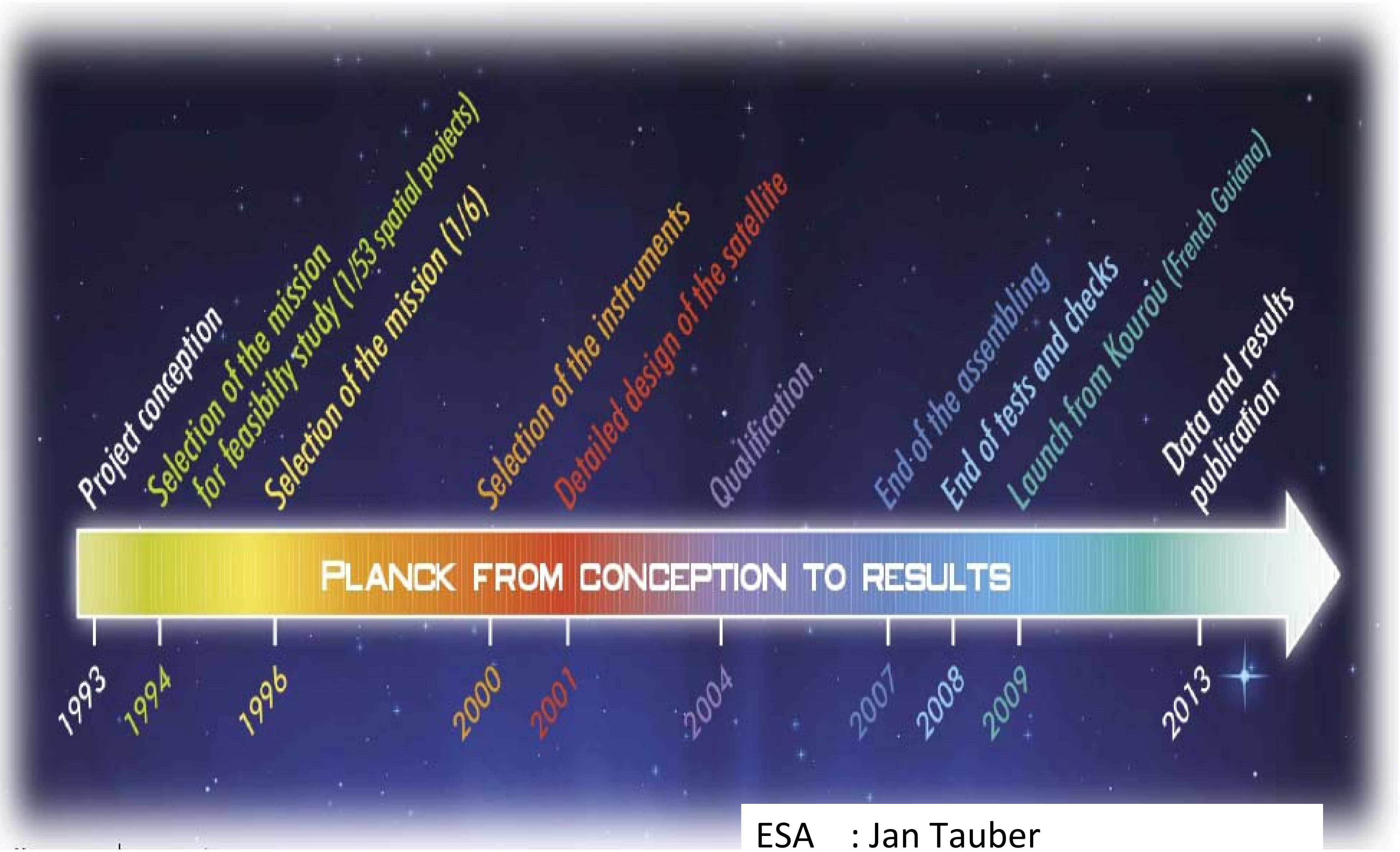


Planck is a very ambitious experiment.

It carries a complex CMB experiment (the state of the art, a few years ago) all the way to L2,

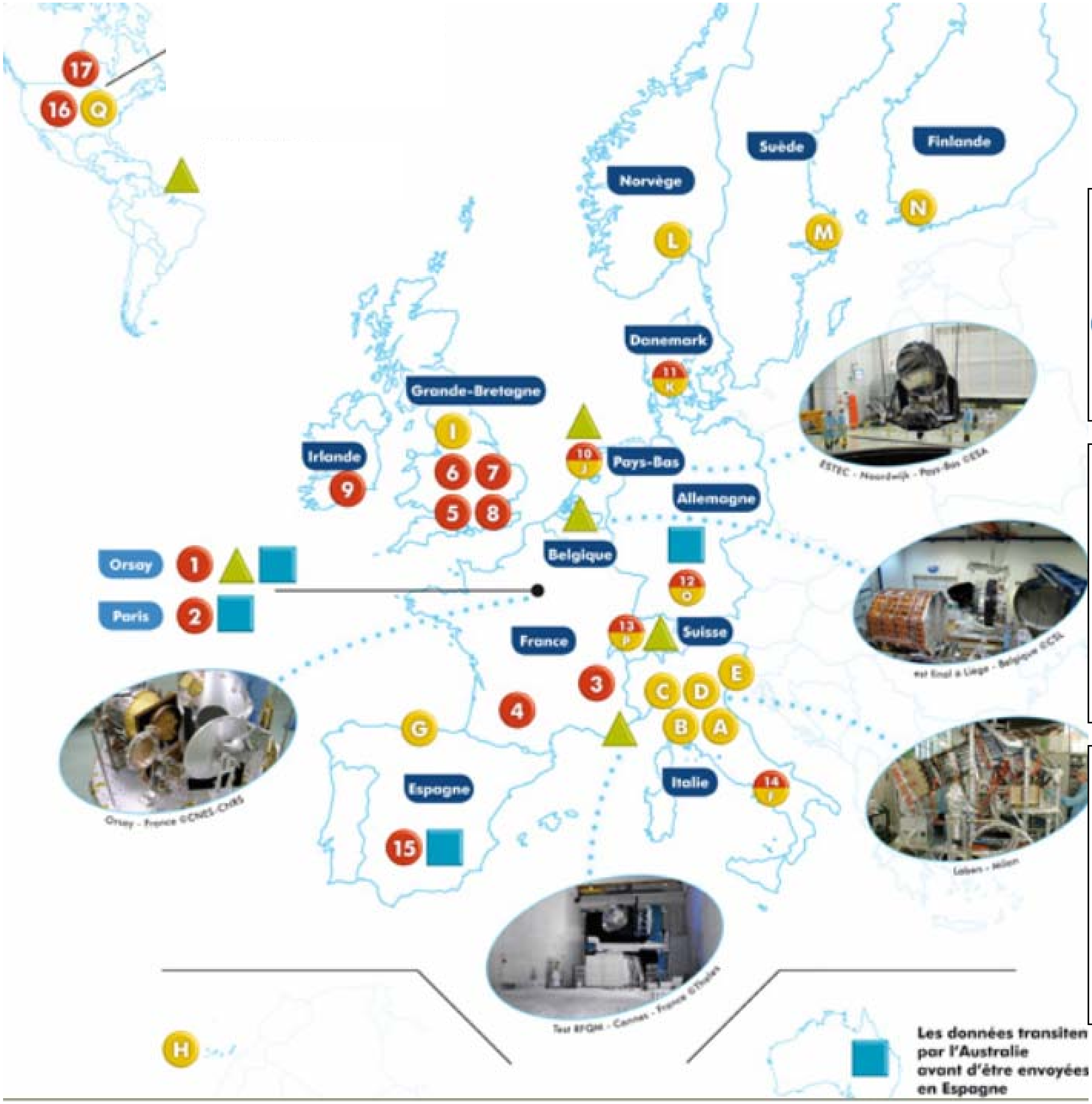
improving the sensitivity wrt WMAP by at least a factor 10,

extending the frequency coverage towards high frequencies by a factor about 10



Almost 20 years of hard work of a very large team, coordinated by:

ESA : Jan Tauber
HFI PI : Jean Loup Puget (Paris)
HFI IS : Jean Michel Lamarre (Paris)
LFI PI : Reno Mandolesi (Bologna)
LFI IS : Marco Bersanelli (Milano)



▲ esa

National Agencies

cnes

asi agenzia spaziale italiana

NASA

Scientific Laboratories

🔴 HFI PI Puget

🟡 LFI PI Mandolesi

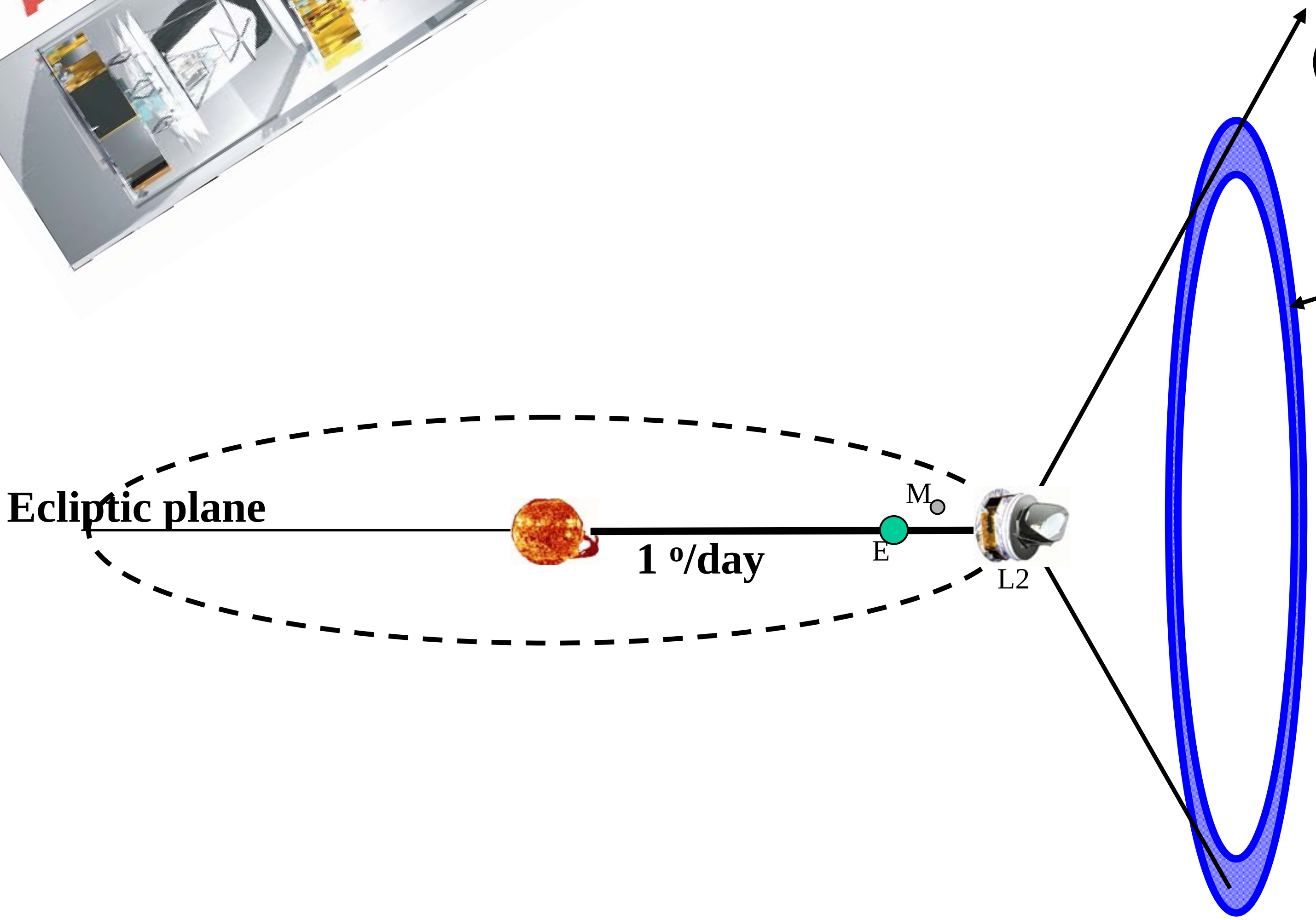
Satellite

ThalesAlenia Space
A Thales / Finmeccanica Company

+ subcontractors

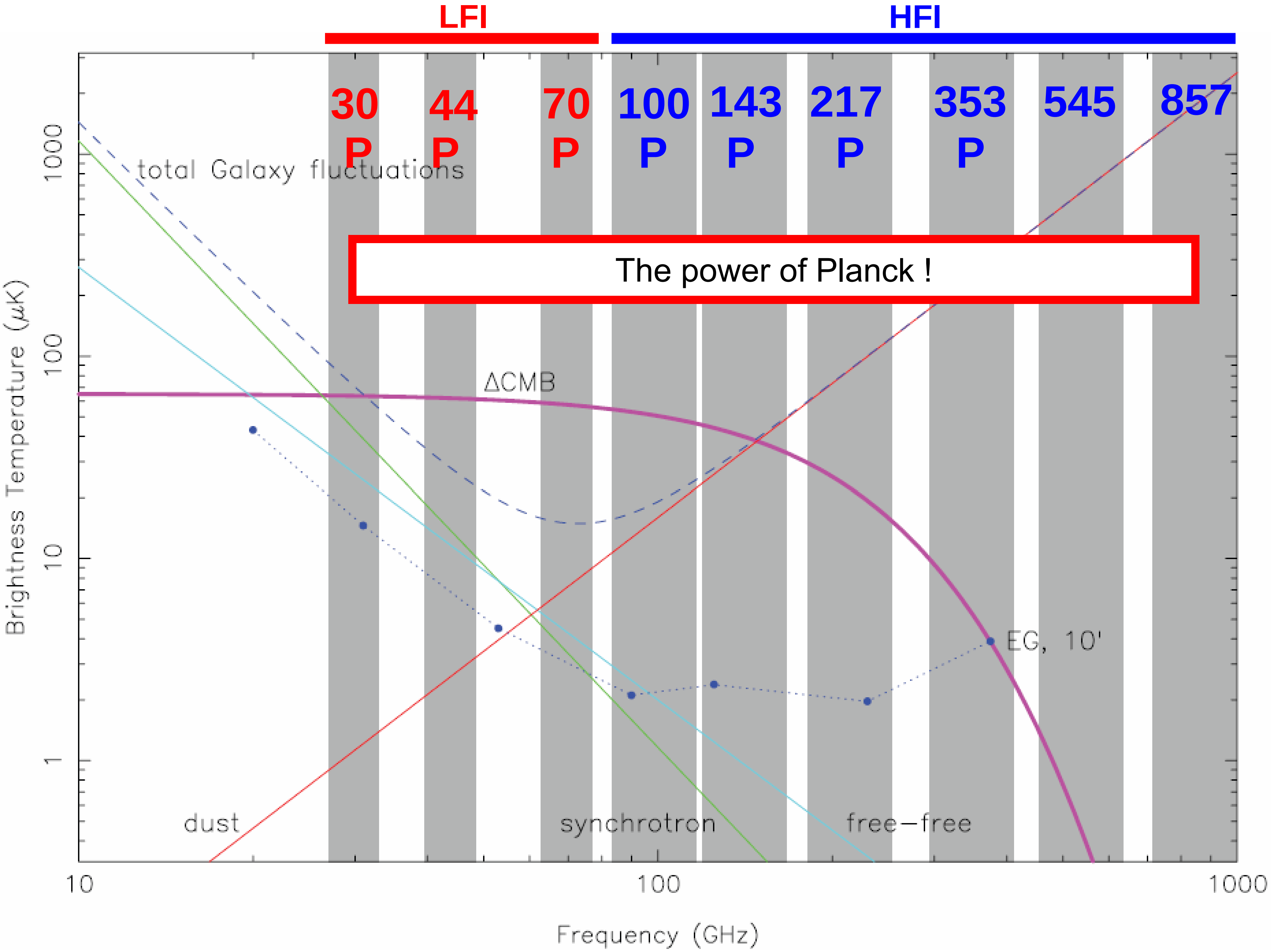
Observing strategy

The payload works in L2, to avoid the emission of the Earth, of the Moon, of the Sun

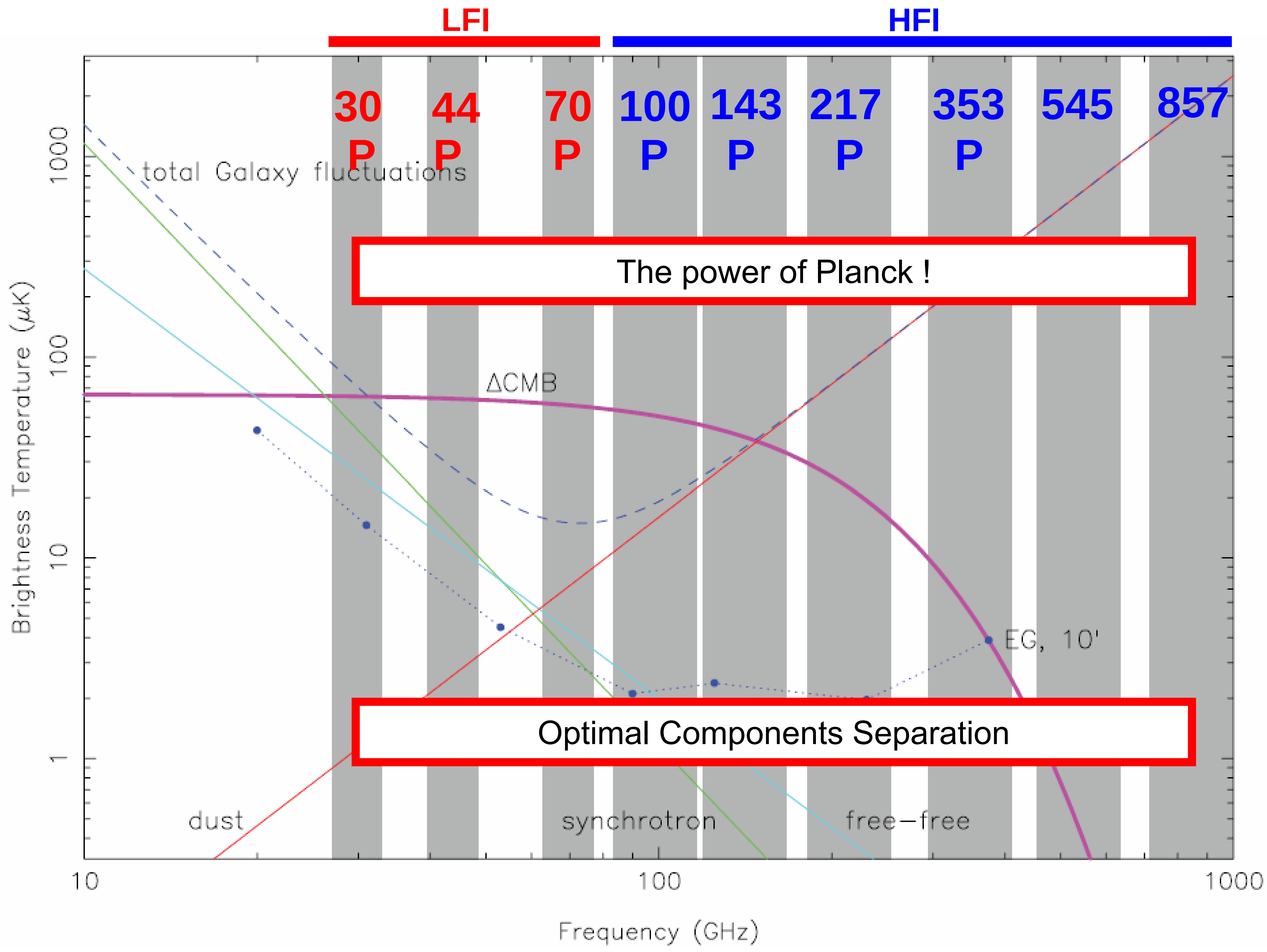


Boresight
(85° from spin axis)

Field of view
rotates at 1 rpm



The power of Planck !

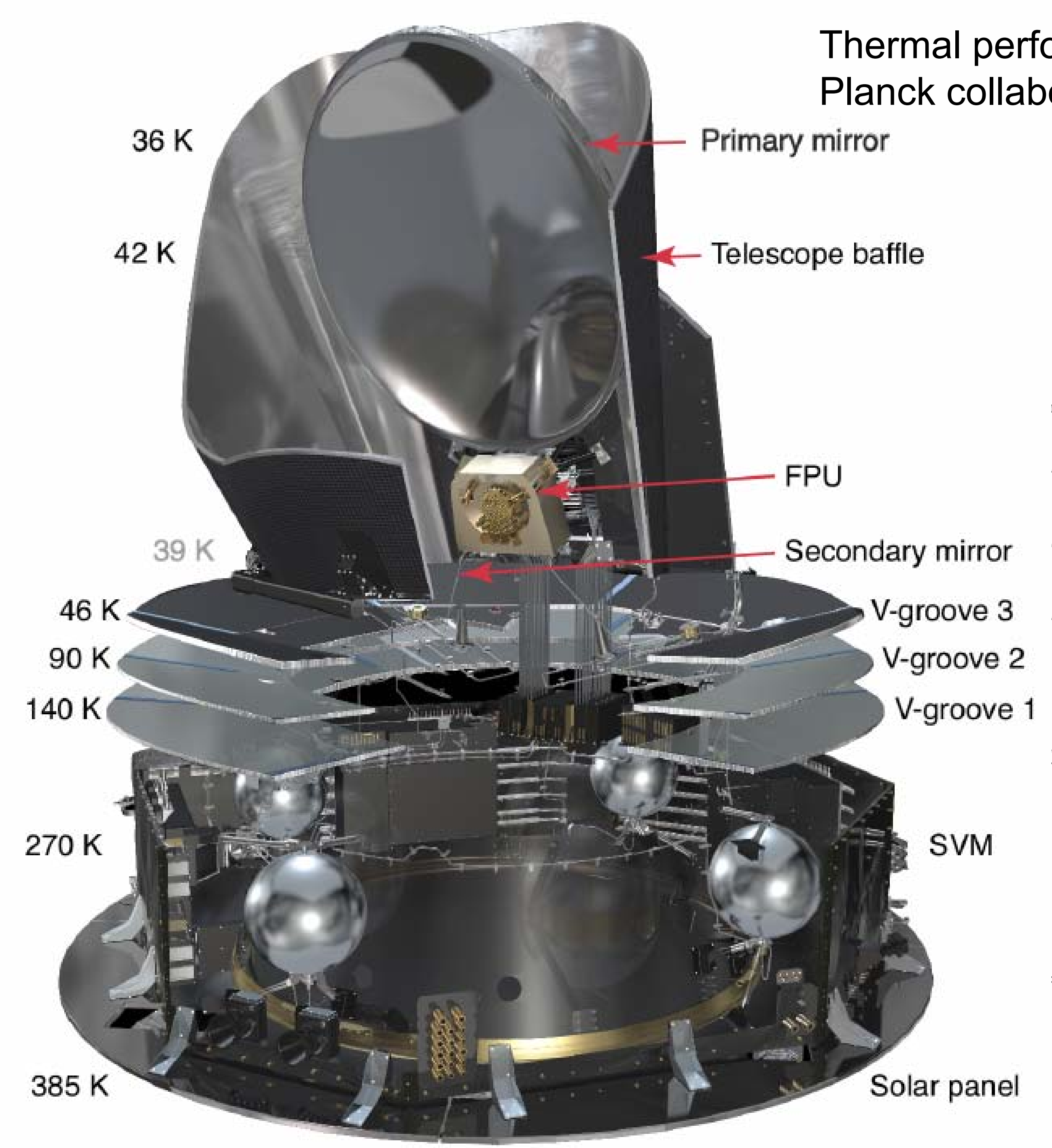


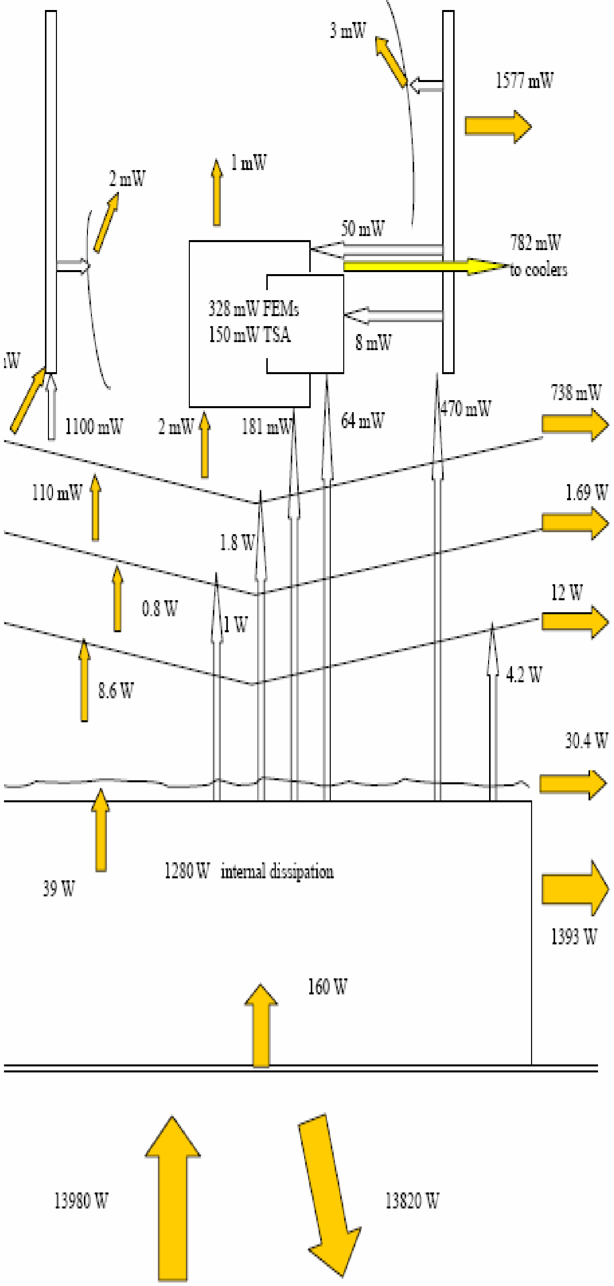
The power of Planck !

Optimal Components Separation

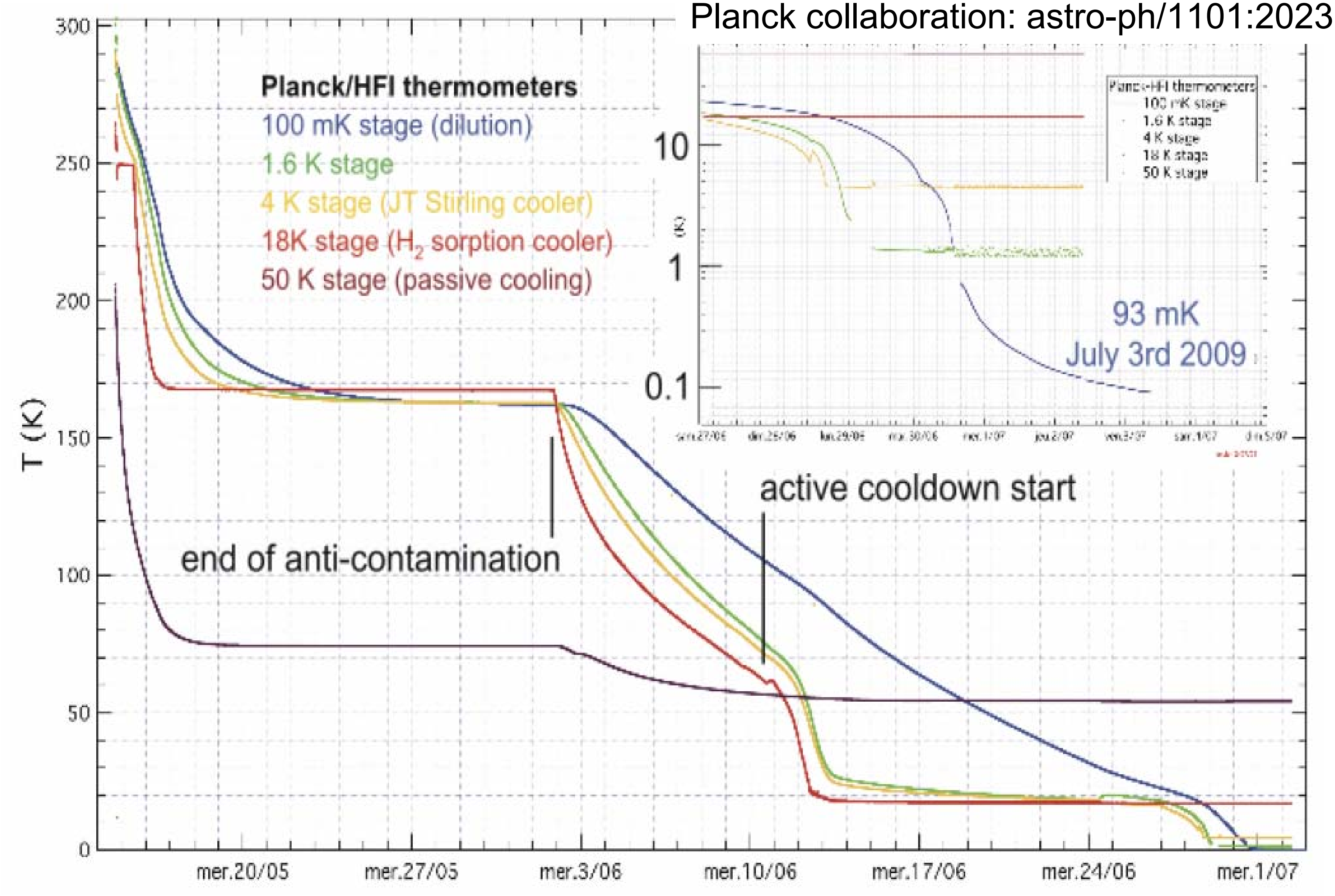
14 / May / 2009

Thermal performance :
Planck collaboration: astro-ph/1101:2023





Thermal performance :
Planck collaboration: astro-ph/1101:2023



end of anti-contamination

active cooldown start

93 mK
July 3rd 2009

Mission :
Planck collaboration: astro-ph/1101:2022

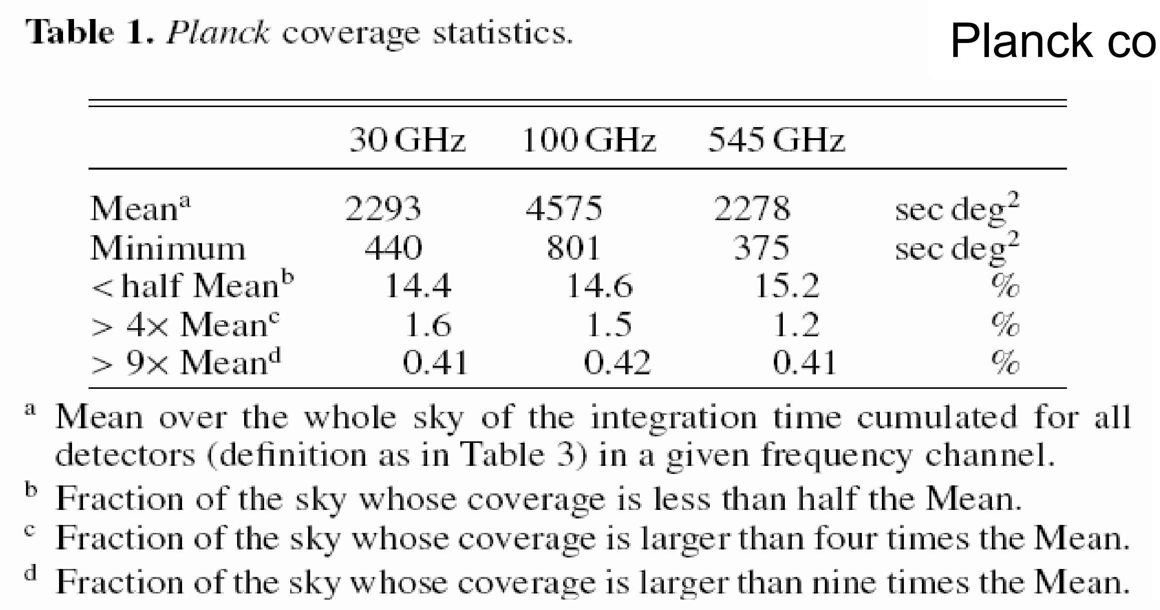


Table 1. *Planck* coverage statistics.

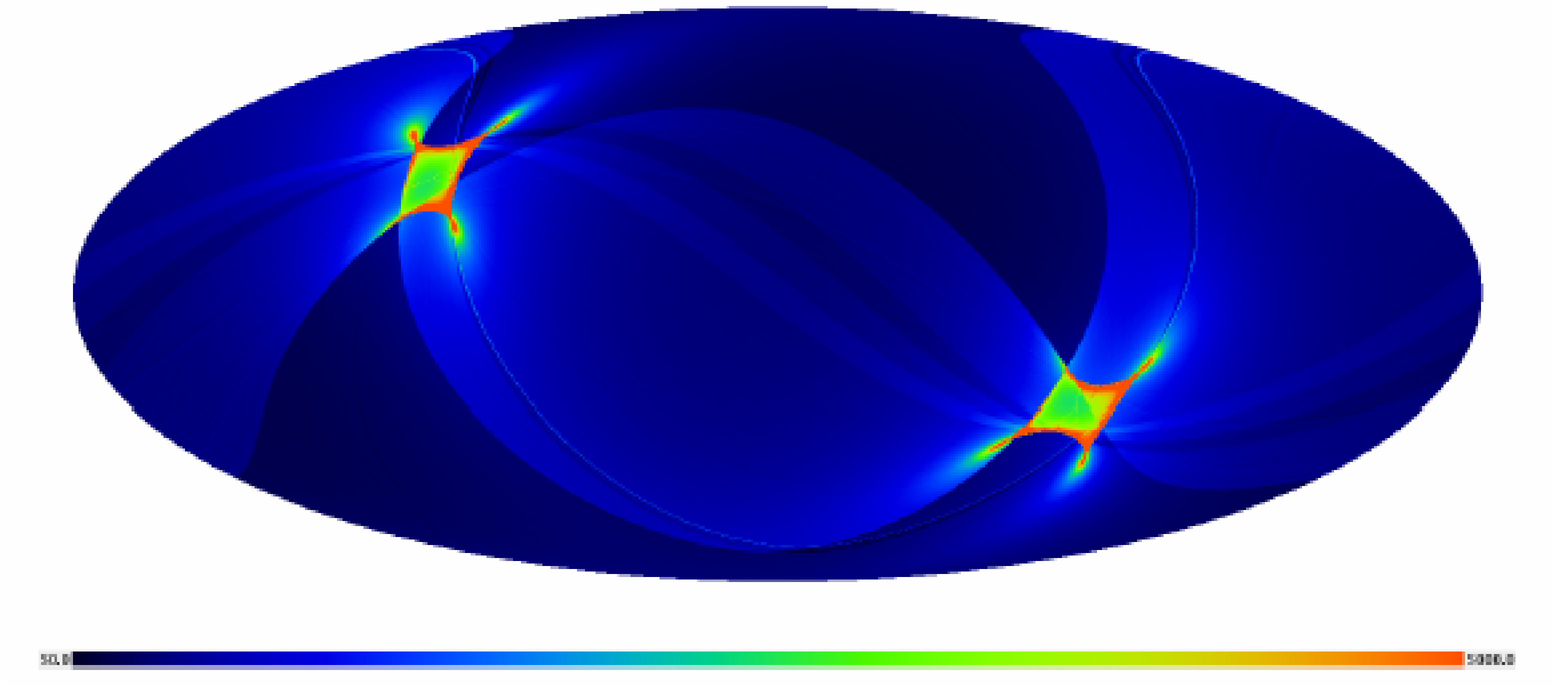
	30 GHz	100 GHz	545 GHz	
Mean[a]	2293	4575	2278	sec deg^2
Minimum	440	801	375	sec deg^2
< half Mean[b]	14.4	14.6	15.2	%
> 4× Mean[c]	1.6	1.5	1.2	%
> 9× Mean[d]	0.41	0.42	0.41	%

[a] Mean over the whole sky of the integration time cumulated for all detectors (definition as in Table 3) in a given frequency channel.

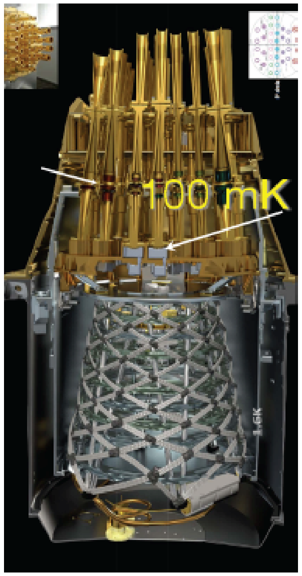
[b] Fraction of the sky whose coverage is less than half the Mean.

[c] Fraction of the sky whose coverage is larger than four times the Mean.

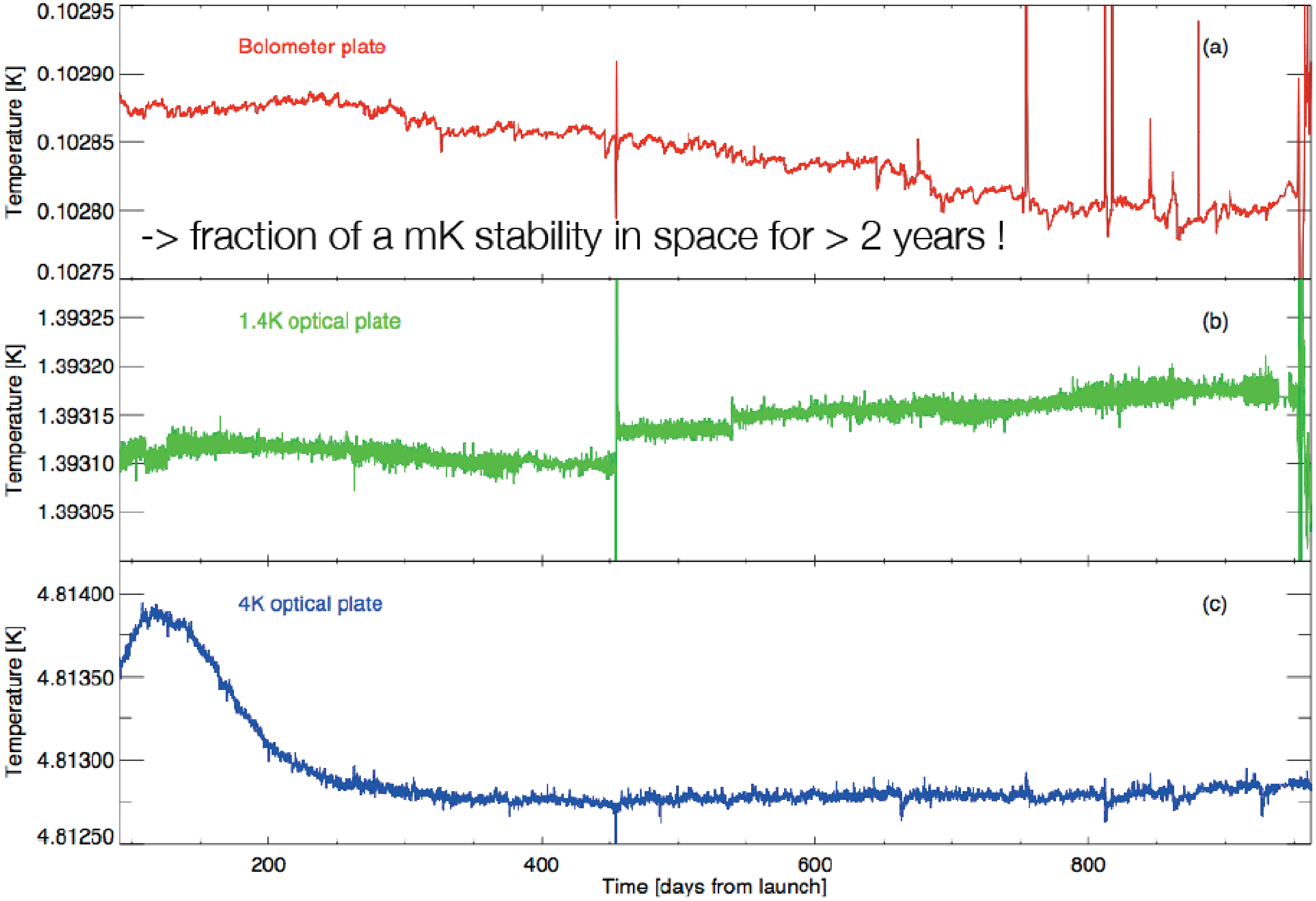
[d] Fraction of the sky whose coverage is larger than nine times the Mean.



A very **stable** environment



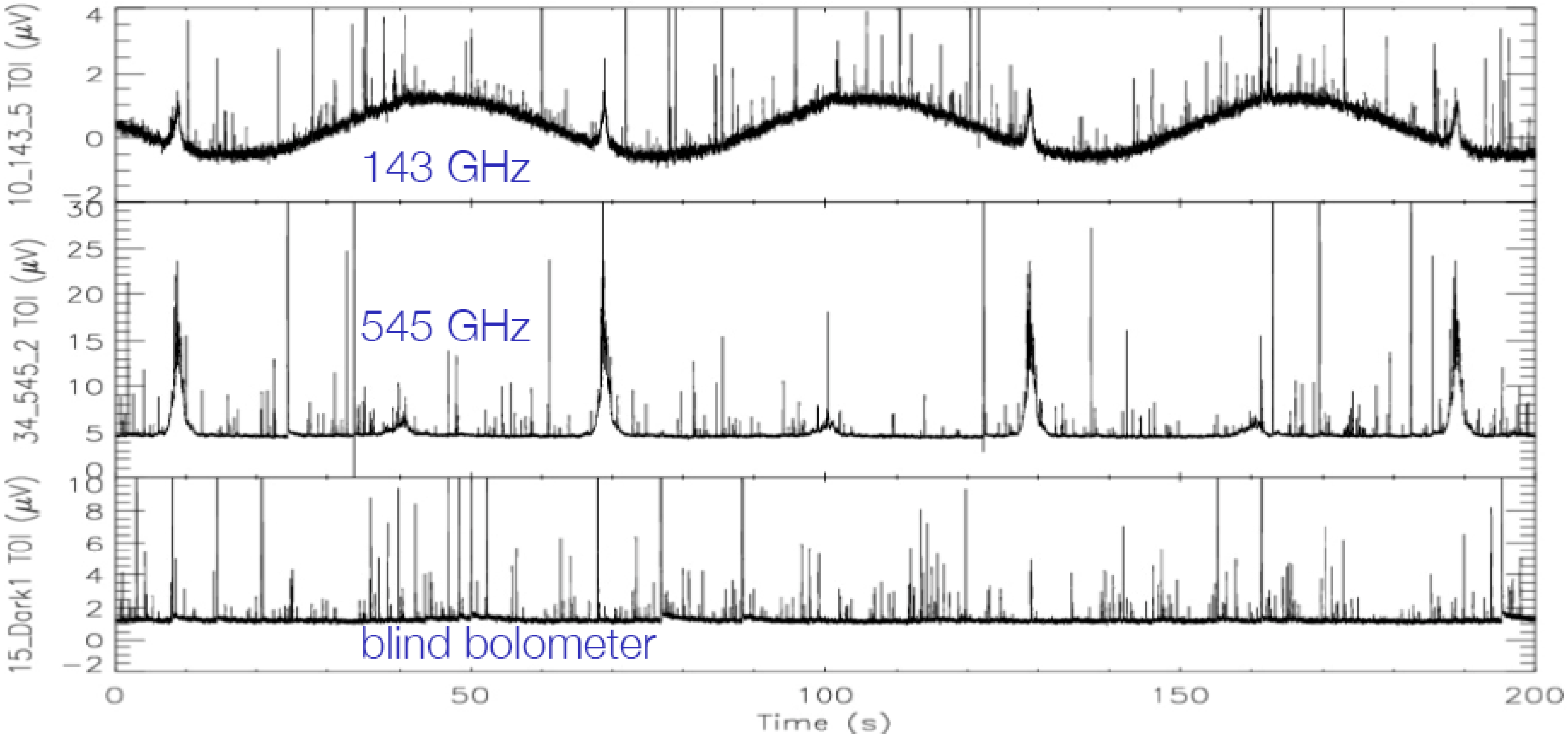
Cryostat:
dilution He3/He4



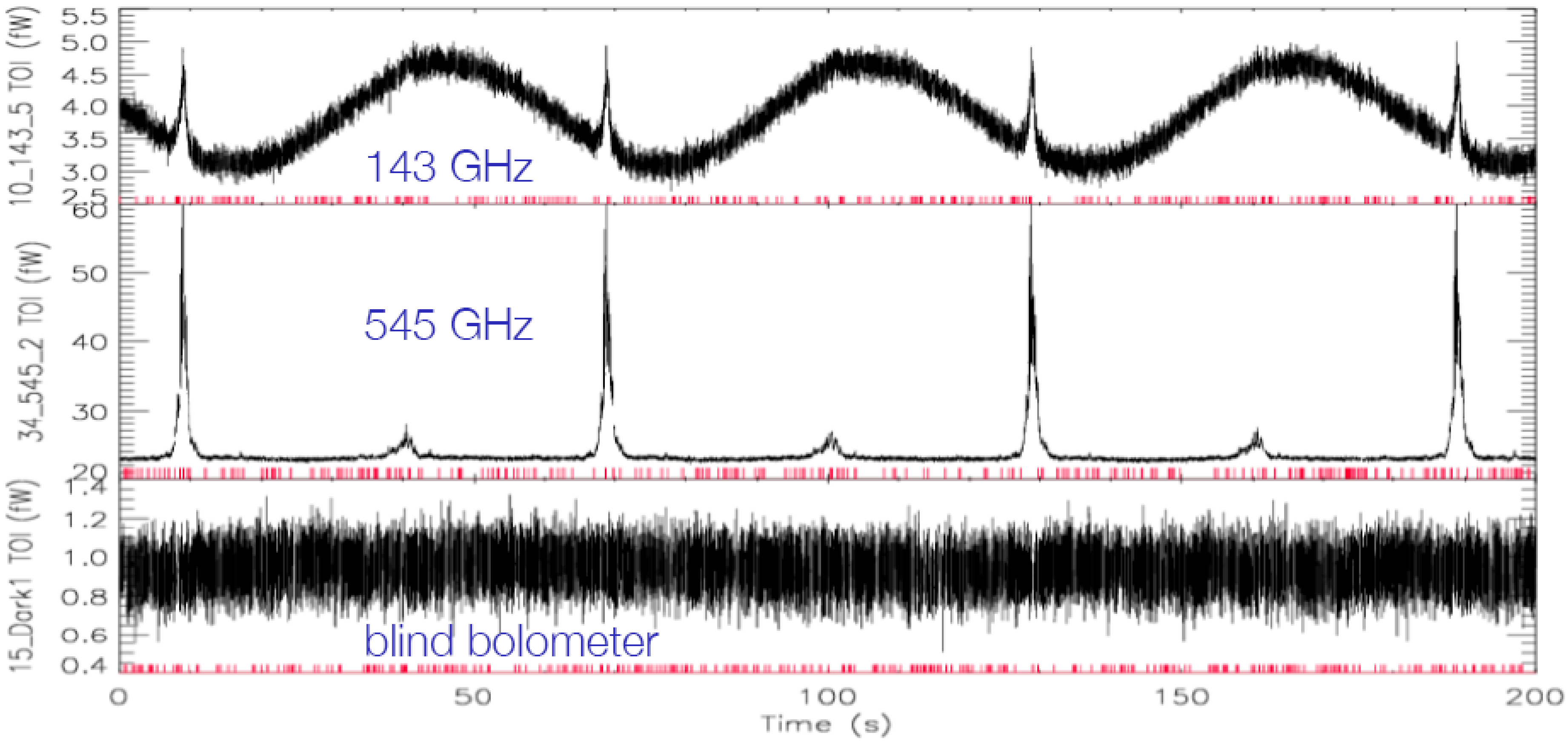
-> fraction of a mK stability in space for > 2 years !

Fig. 7. The impressive stability of the HFI thermal stages during operations. Shown is the temperature evolution of the bolometer stage (*top*), the 1.6 K optical filter stage (*middle*) and the 4-K cooler reference load stage (*bottom*). The horizontal axis displays days since the beginning of the nominal mission.

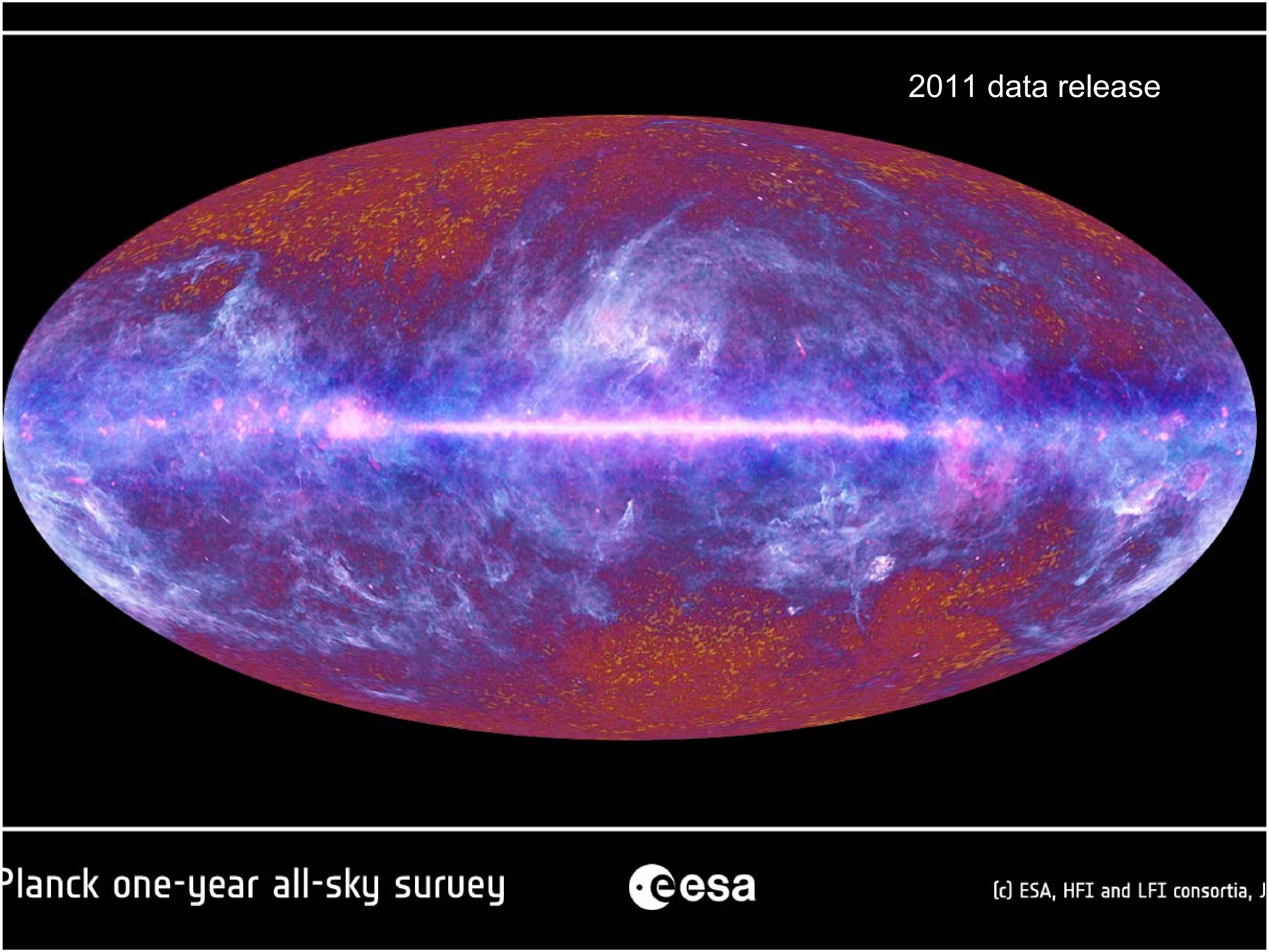
Raw HFI data


10_143_5 TOI (μV)
4
2
0
-2
143 GHz
34_545_2 TOI (μV)
30
25
20
15
10
5
0
545 GHz
15_Dark1 TOI (μV)
10
8
6
4
2
0
-2
blind bolometer
0
50
100
150
200
Time (s)

De-spiked HFI data



<20% of data flagged



2011 data release

Planck one-year all-sky survey

esa

(c) ESA, HFI and LFI consortia, J

The 2013 Planck results

- Planck 2013 results. I. Overview of products and results
- Planck 2013 results. II. Low Frequency Instrument data processing
- Planck 2013 results. III. LFI systematic uncertainties
- Planck 2013 results. IV. LFI beams
- Planck 2013 results. V. LFI calibration
- Planck 2013 results. VI. High Frequency Instrument data processing
- Planck 2013 results. VII. HFI time response and beams
- Planck 2013 results. VIII. HFI calibration and mapmaking
- Planck 2013 results. IX. HFI spectral response
- Planck 2013 results. X. HFI energetic particle effects
- Planck 2013 results. XI. Consistency of the data
- Planck 2013 results. XII. Component separation
- Planck 2013 results. XIII. Galactic CO emission
- Planck 2013 results. XIV. Zodiacal emission
- Planck 2013 results. XV. CMB power spectra and likelihood
- Planck 2013 results. XVI. Cosmological parameters
- Planck 2013 results. XVII. Gravitational lensing by large-scale structure
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- Planck 2013 results. XIX. The integrated Sachs-Wolfe effect
- Planck 2013 results. XX. Cosmology from Sunyaev- Zeldovich cluster counts
- Planck 2013 results. XXI. All-sky Compton-parameter map and characterization
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- Planck 2013 results. XXV. Searches for cosmic strings and other topological defects
- Planck 2013 results. XXVI. Background geometry and topology of the Universe
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- Planck 2013 results. XXVIII. The Planck Catalogue of Compact Sources
- Planck 2013 results. XXIX. The Planck catalogue of Sunyaev-Zeldovich sources
- Planck 2013 results. Explanatory supplement

29 papers (+1 to come on CIB);
800+ pages
1 Explanatory Supplement
all products available online

The 2013 Planck results

Instruments, processing, systematic effects

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Components separation

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Power Spectra, cosmological parameters

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Constraints on cosmology

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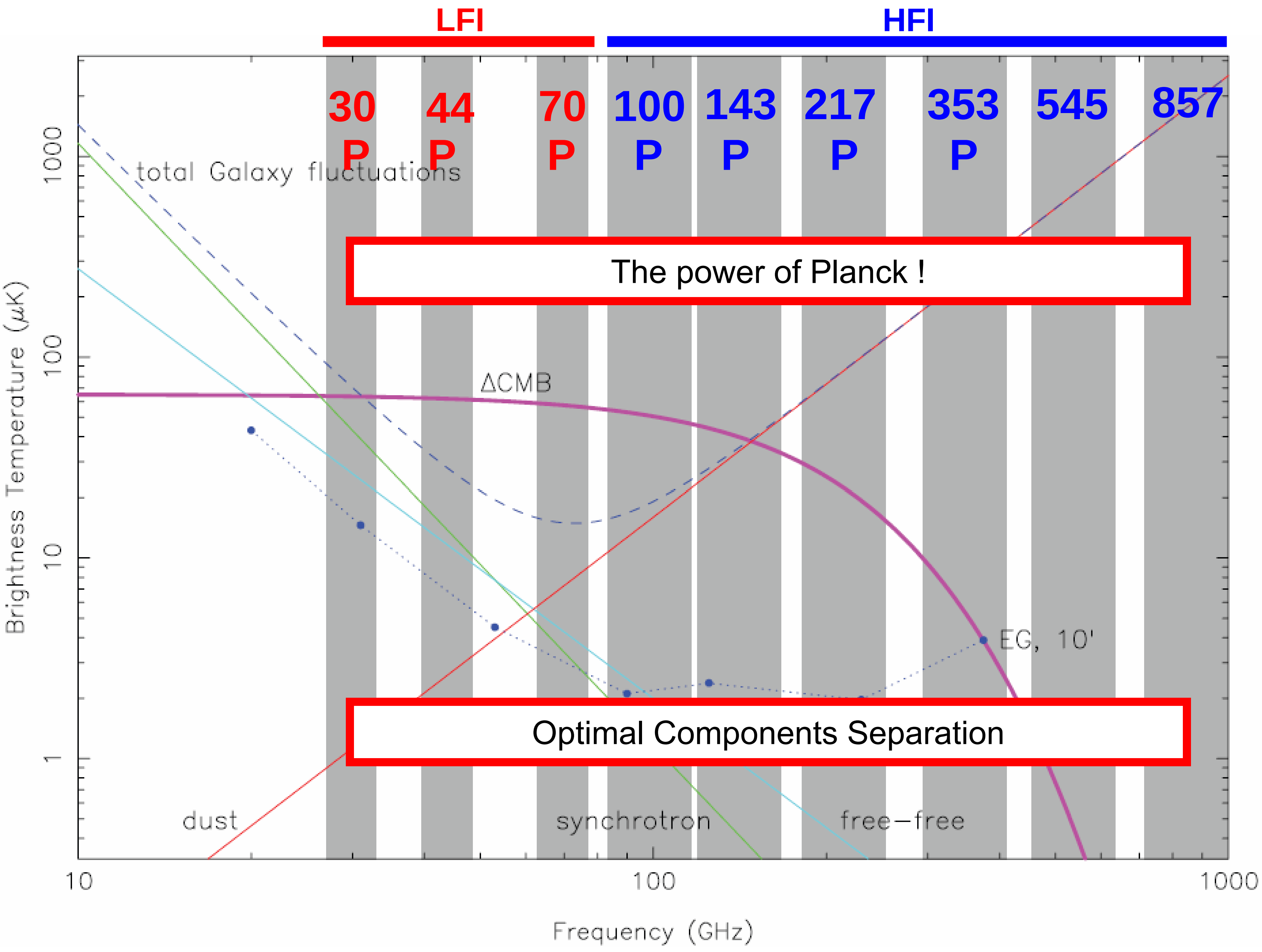
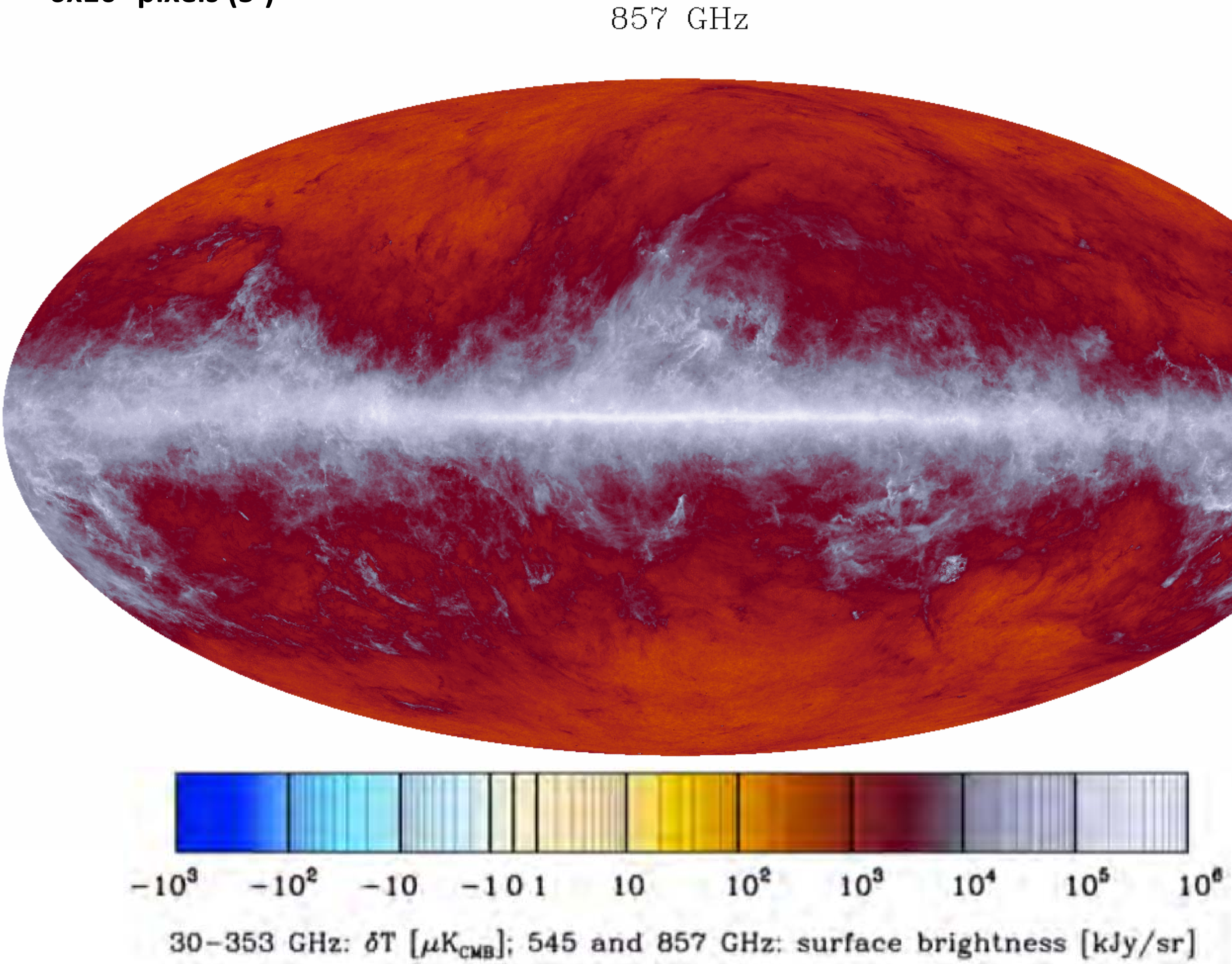


The power of Planck !

Optimal Components Separation

Planck Legacy Maps

$6x10^6$ pixels (5’)



857 GHz

components separation

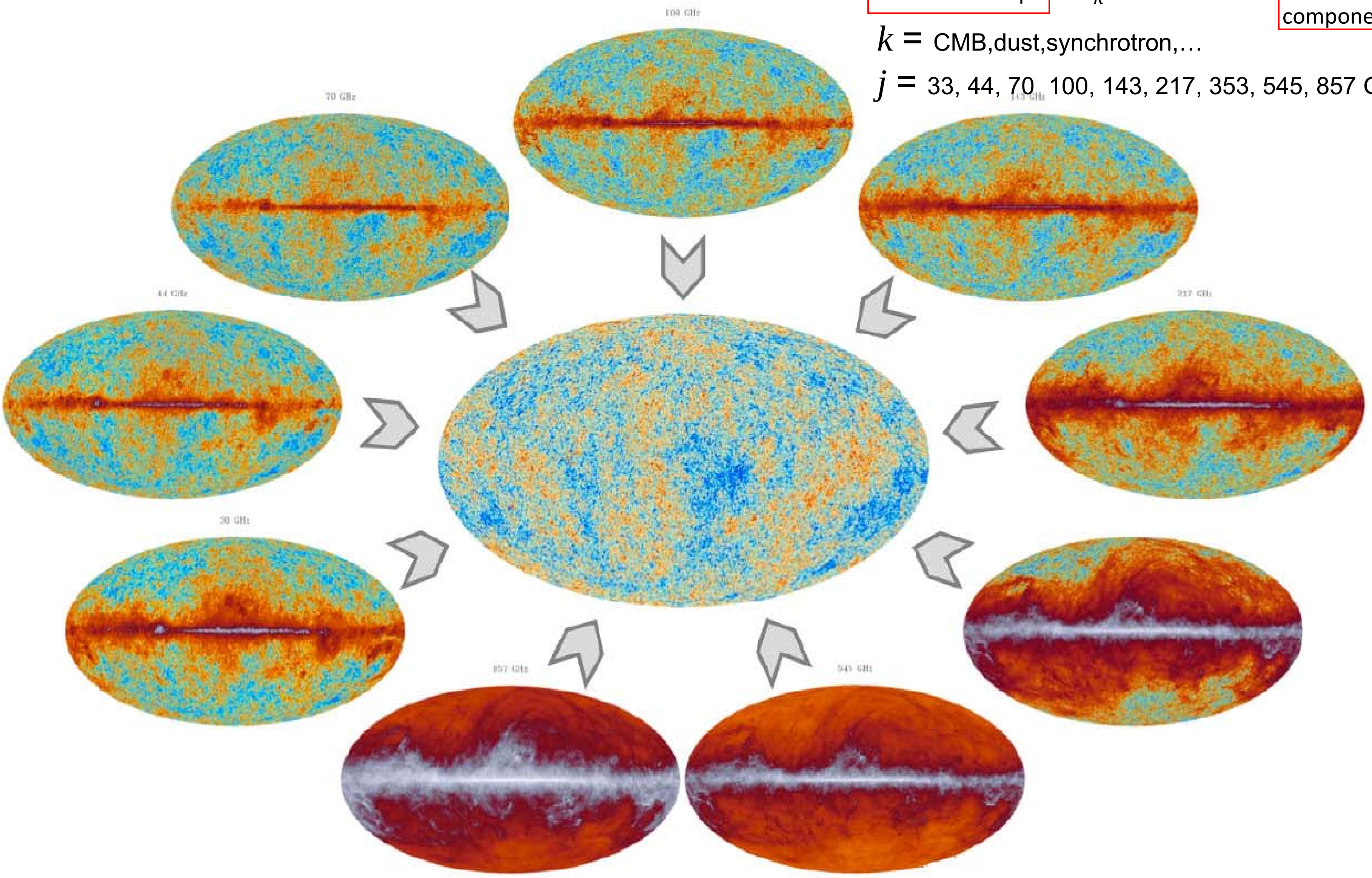
$$\boxed{\Delta T(\nu_j,\ell,b)} = \sum_k a_k(\nu_j,\ell,b)\,\boxed{C_k(\ell,b)}$$

Measured maps

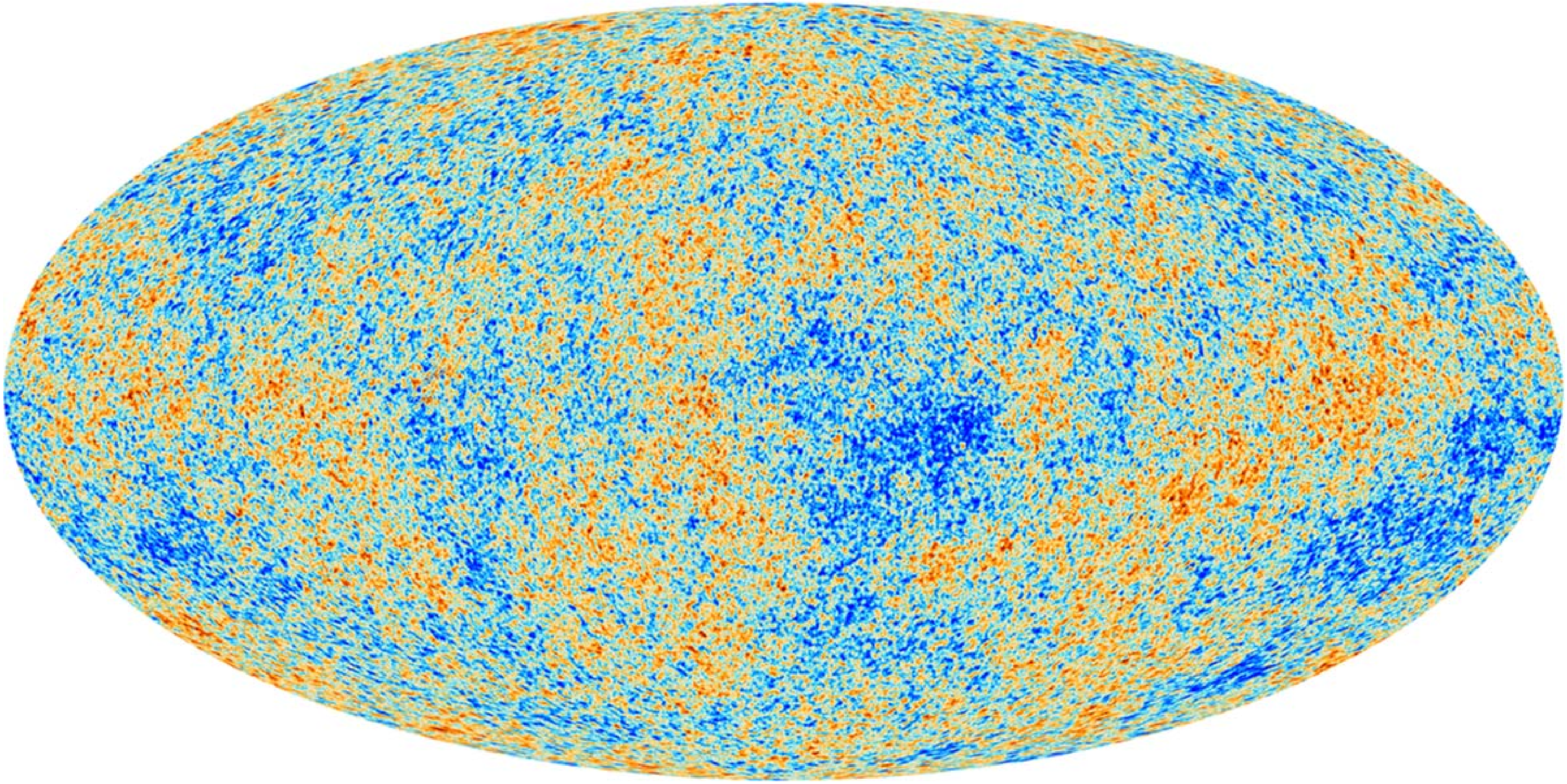
physical components

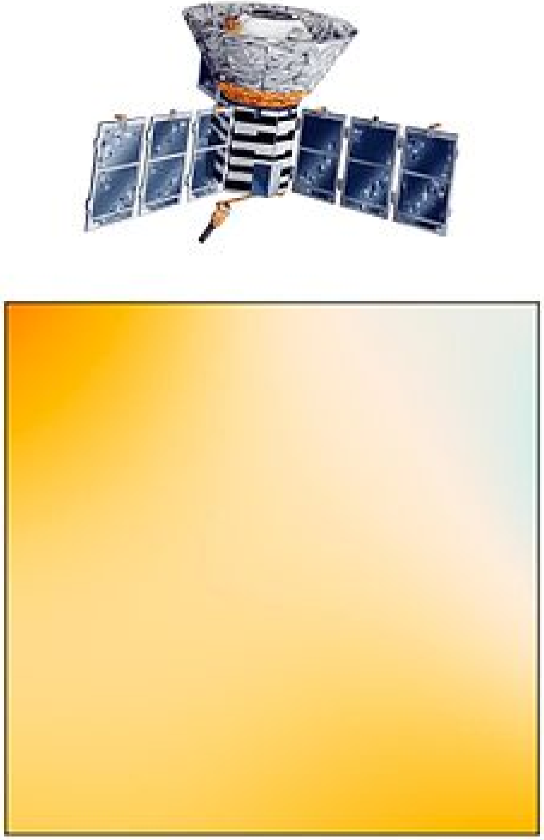
k = CMB,dust,synchrotron,…

j = 33, 44, 70, 100, 143, 217, 353, 545, 857 GHz

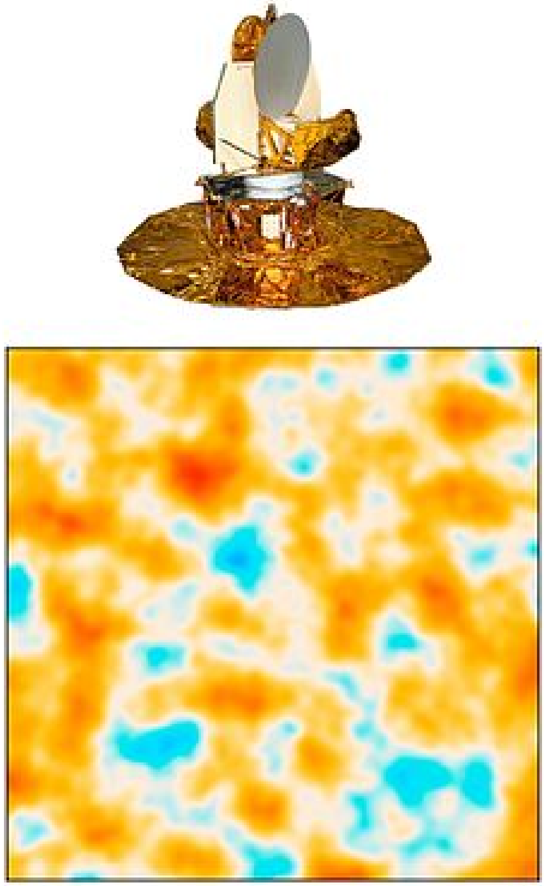


The CMB component

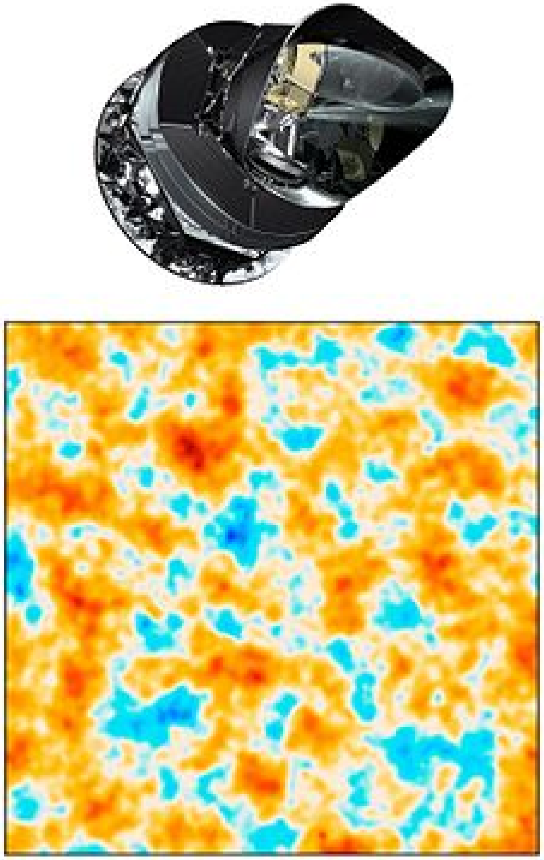




COBE

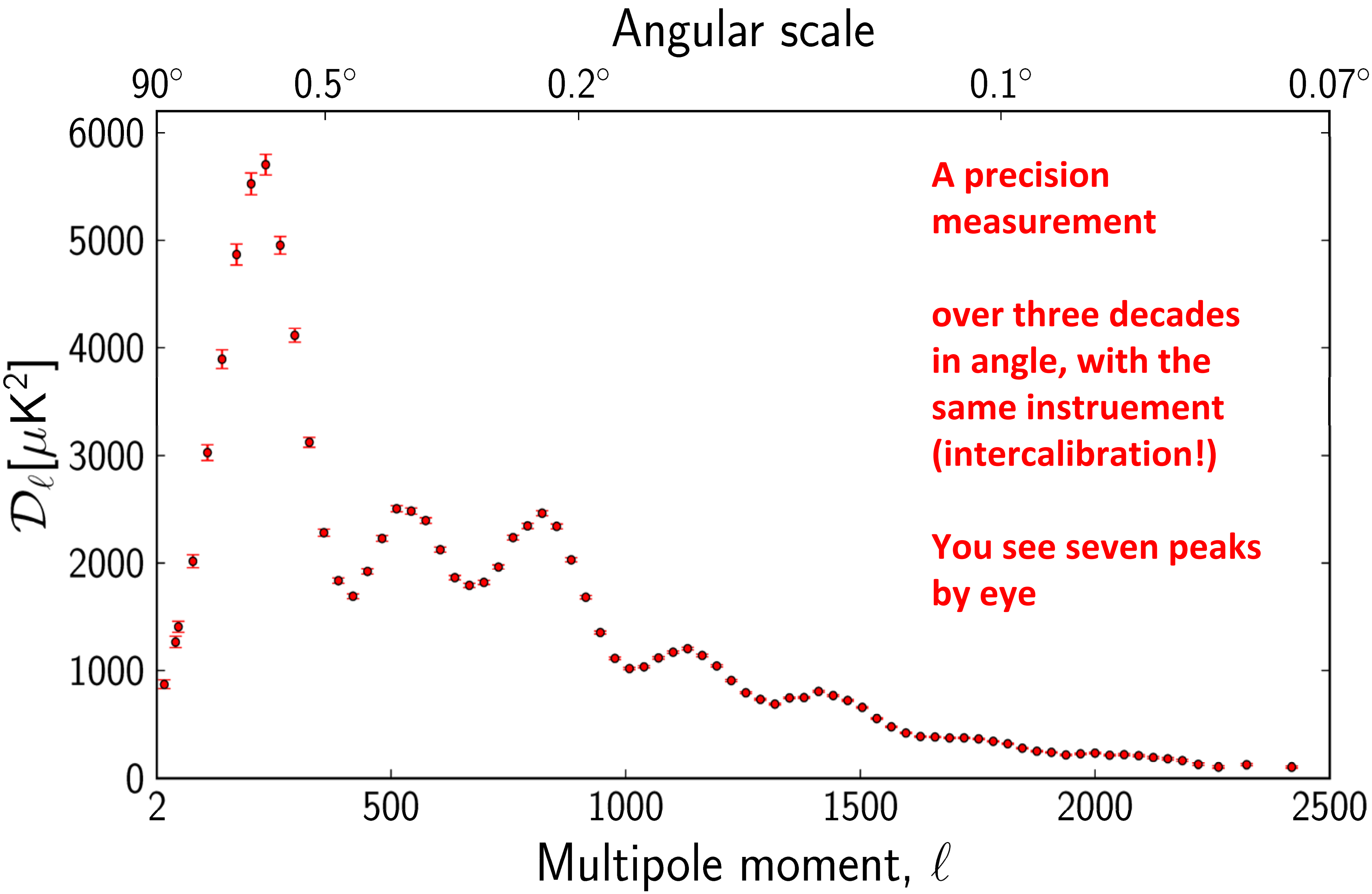


WMAP



Planck

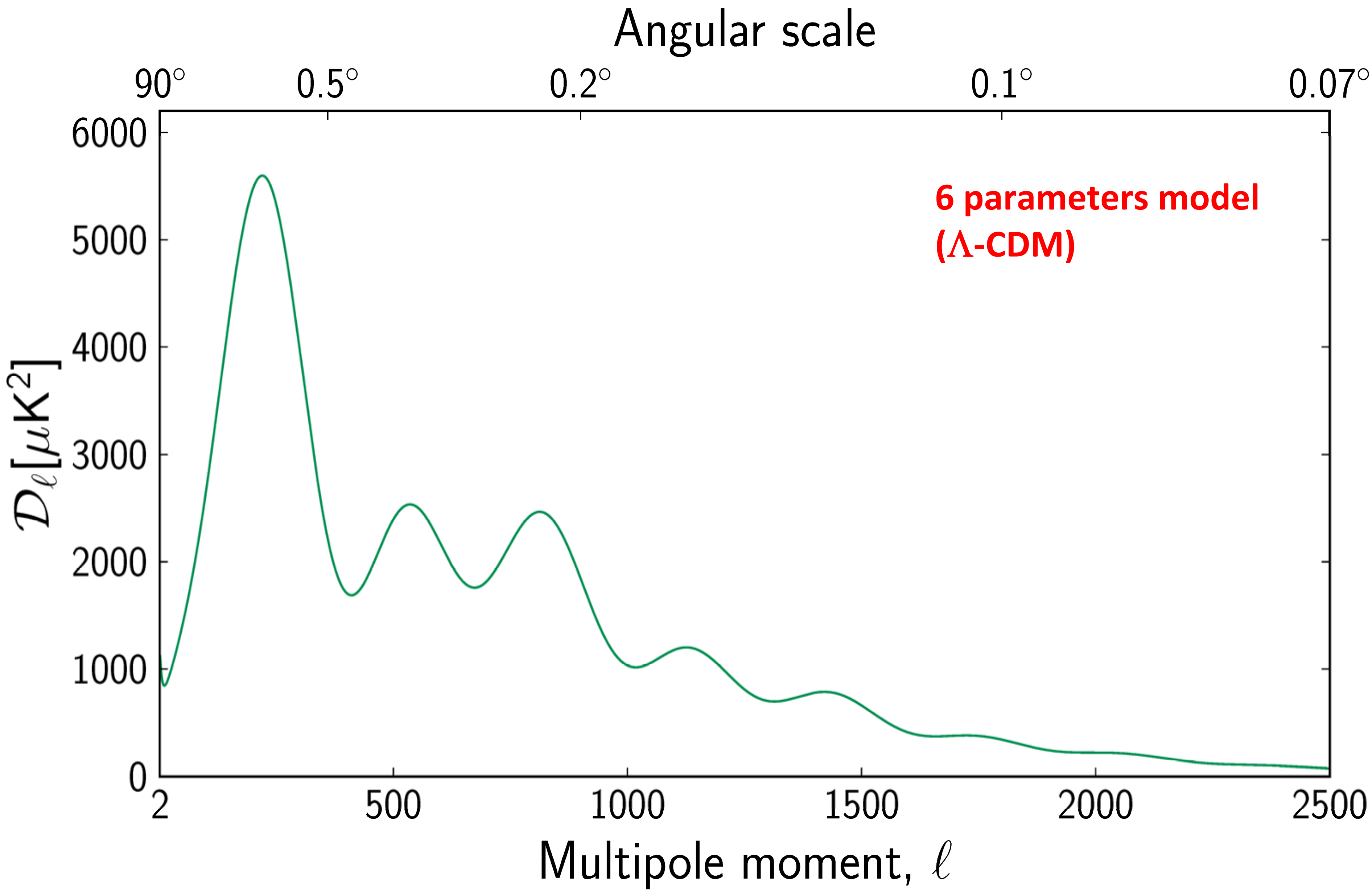
Best angular resolution
Best control of foregorunds



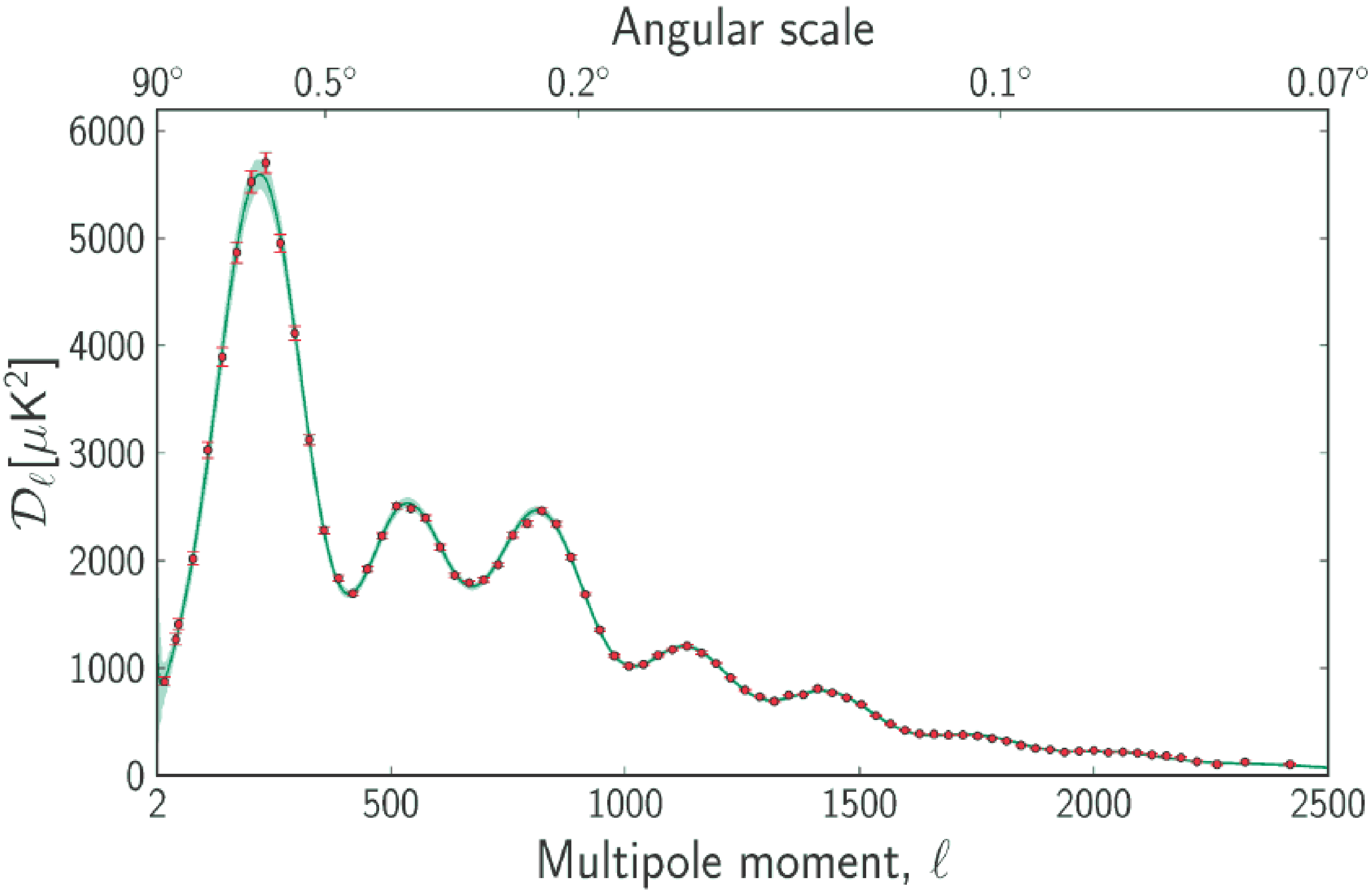
A precision measurement

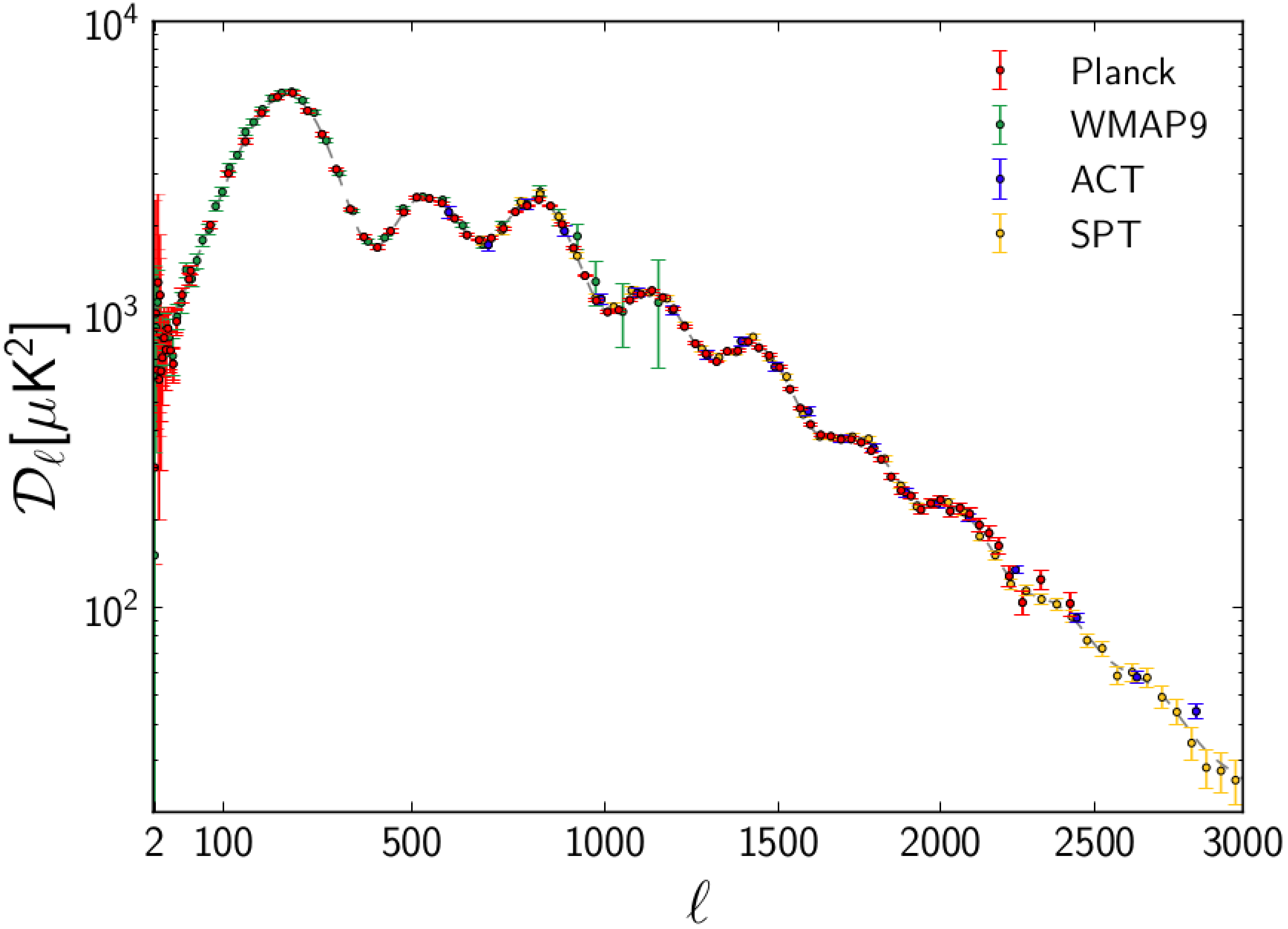
over three decades in angle, with the same instruement (intercalibration!)

You see seven peaks by eye



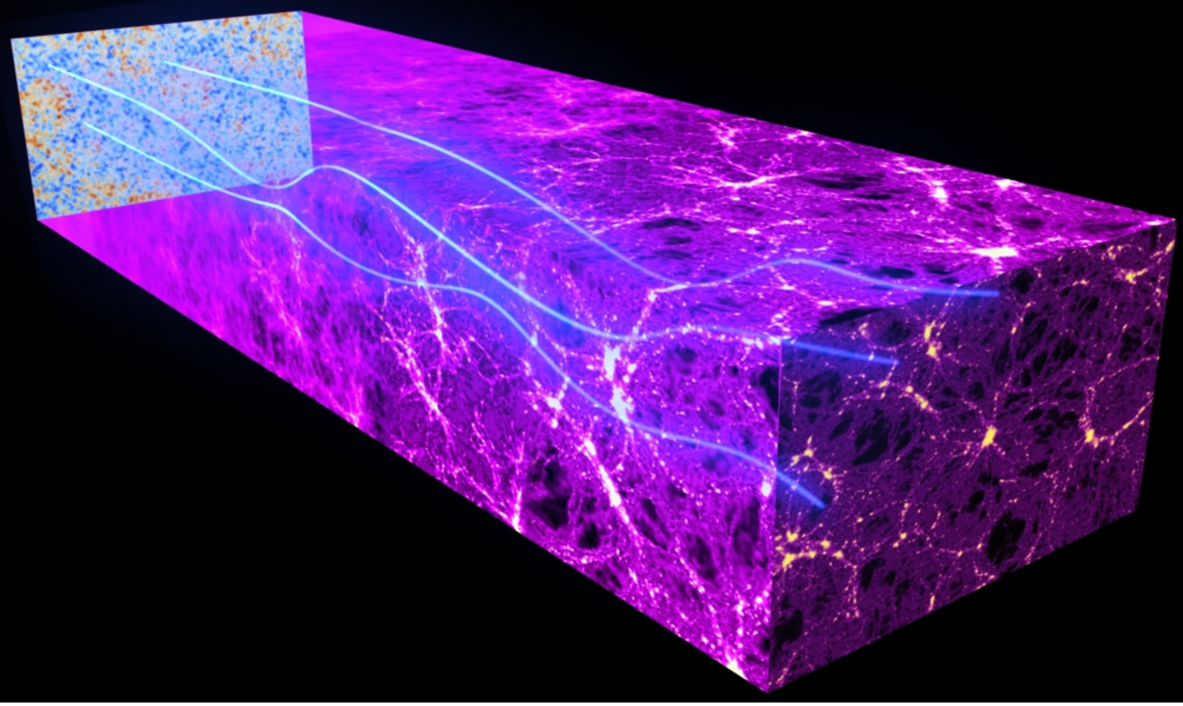
6 parameters model
(Λ-CDM)


Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ

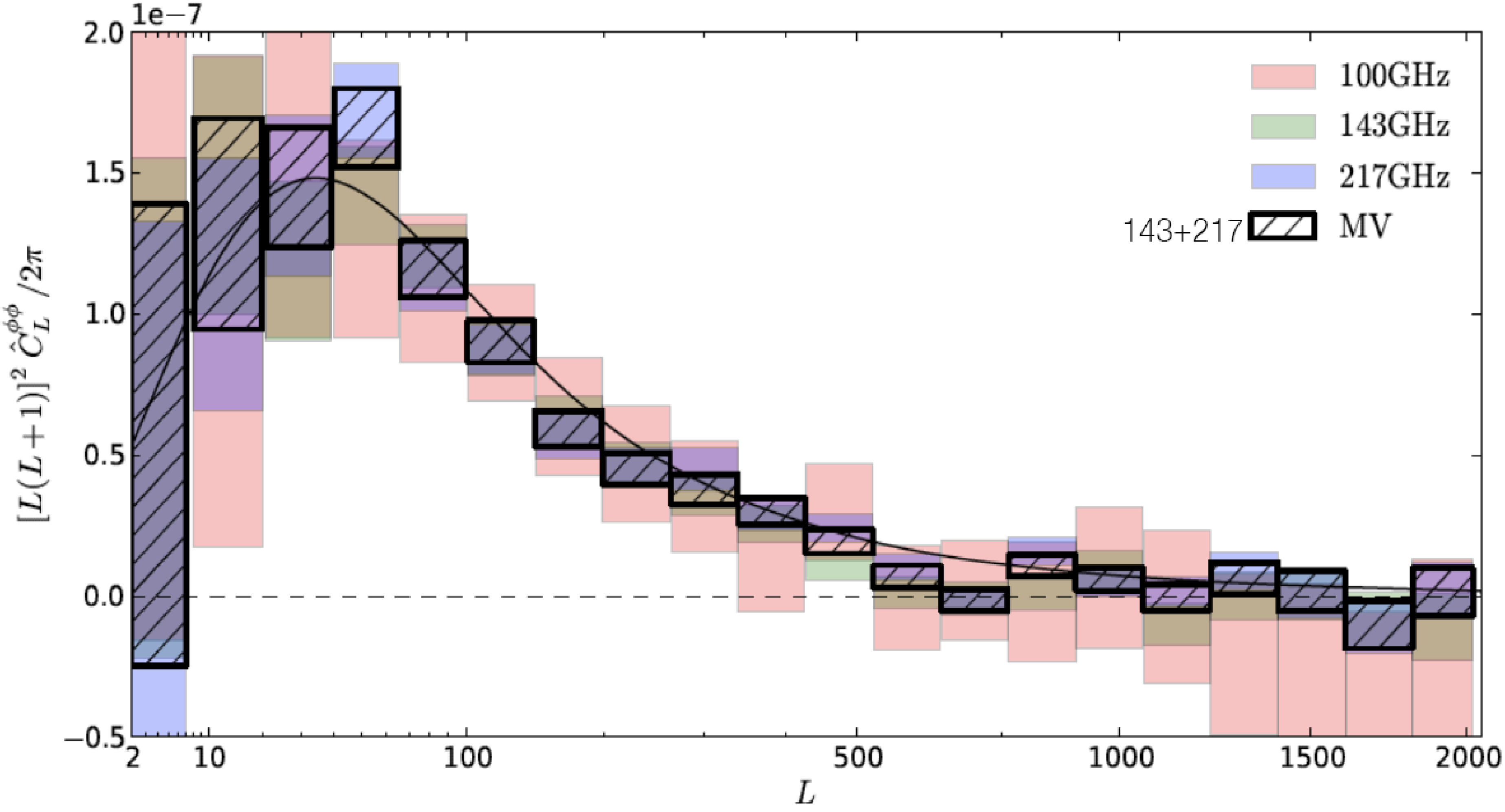

10^4
10^3
10^2
$\mathcal{D}_\ell [\mu K^2]$
2
100
500
1000
1500
2000
2500
3000
ℓ
Planck
WMAP9
ACT
SPT

CMB anisotropy (lensing)

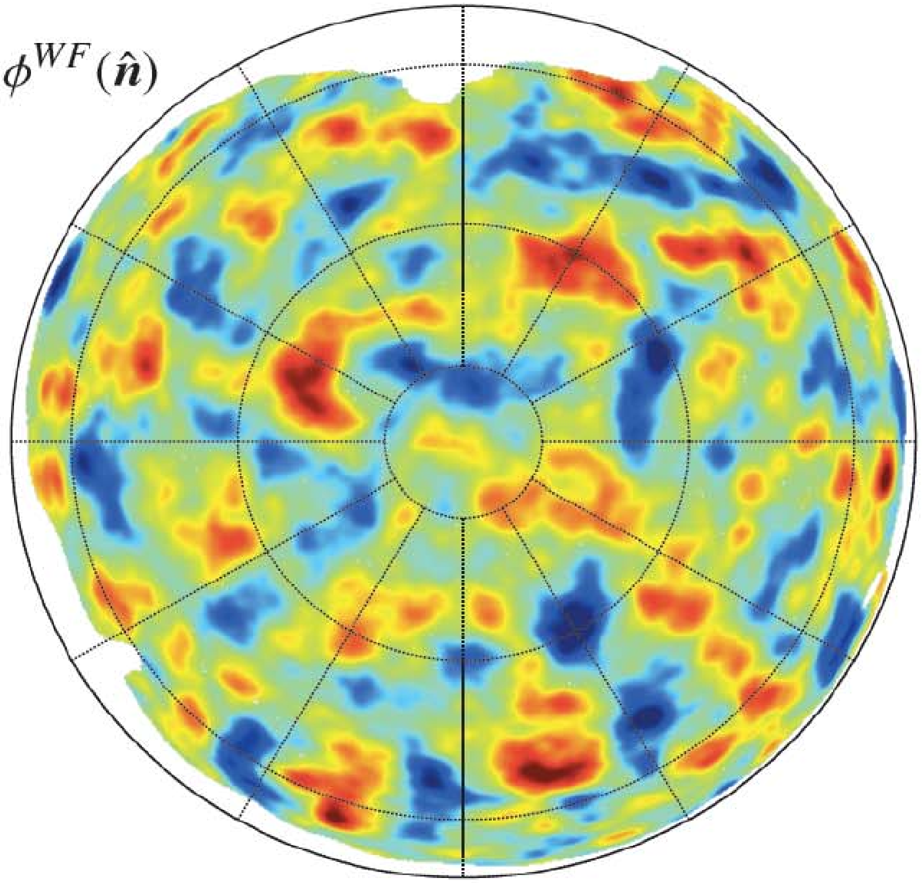
- Photons travelling in the universe for 13.7 Gly interact with massive structures, and are deflected (gravitational lensing)
- The result is a modified image of CMB anisotropy, which can be analyzed to study the distribution of mass (mainly dark matter) all the way to recombination.



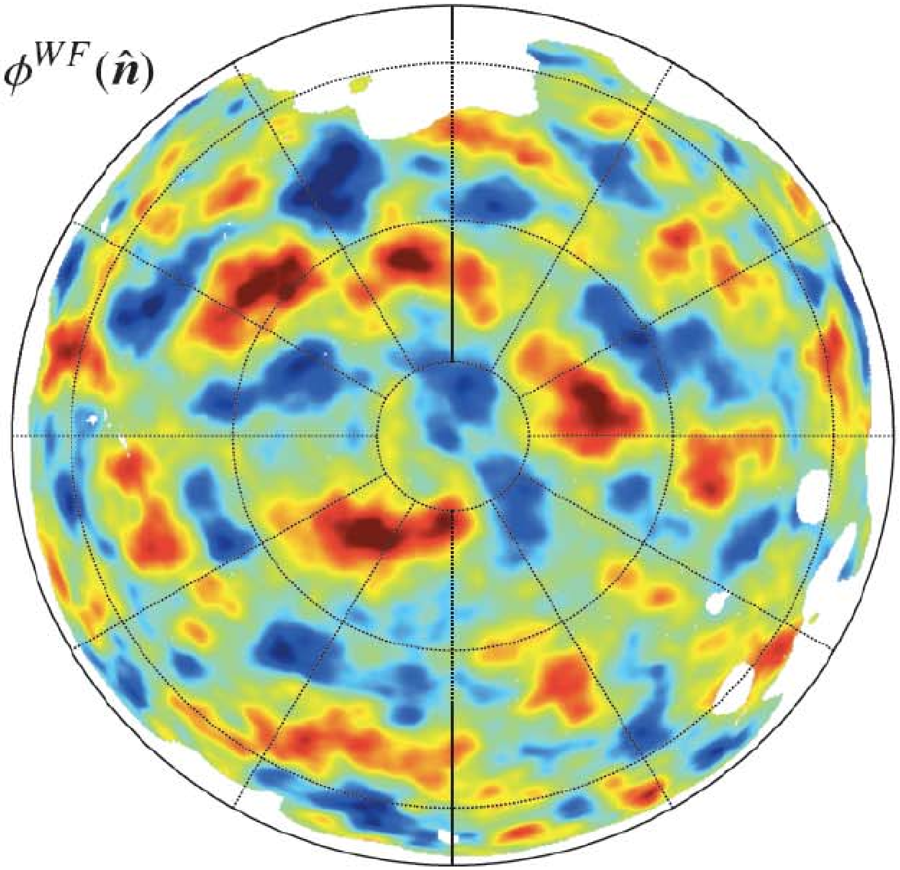
Power spectrum of deflections



All-sky map of dark matter

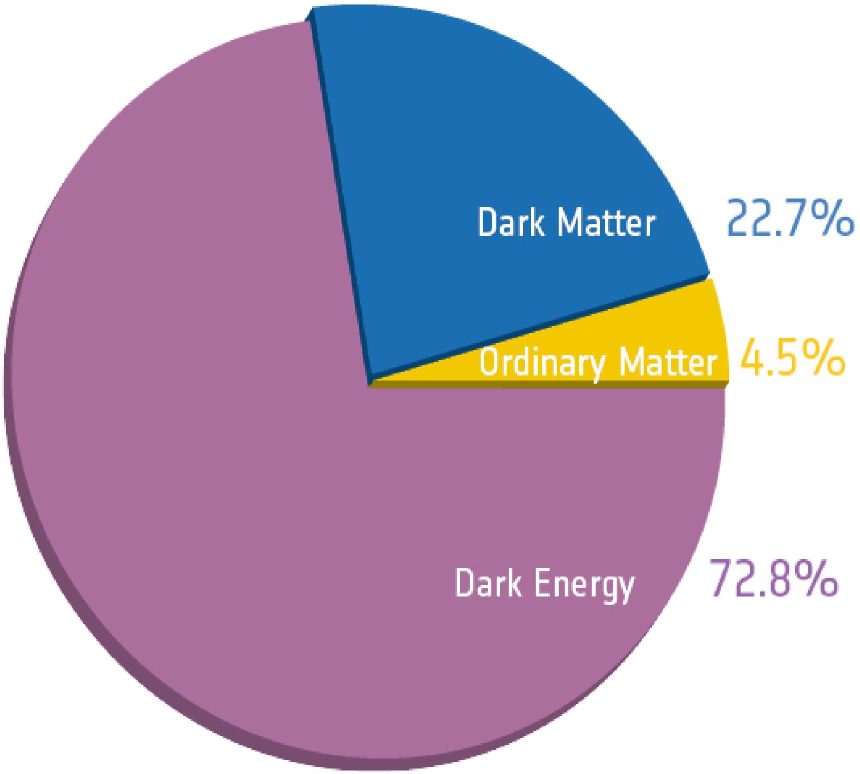


Galactic North

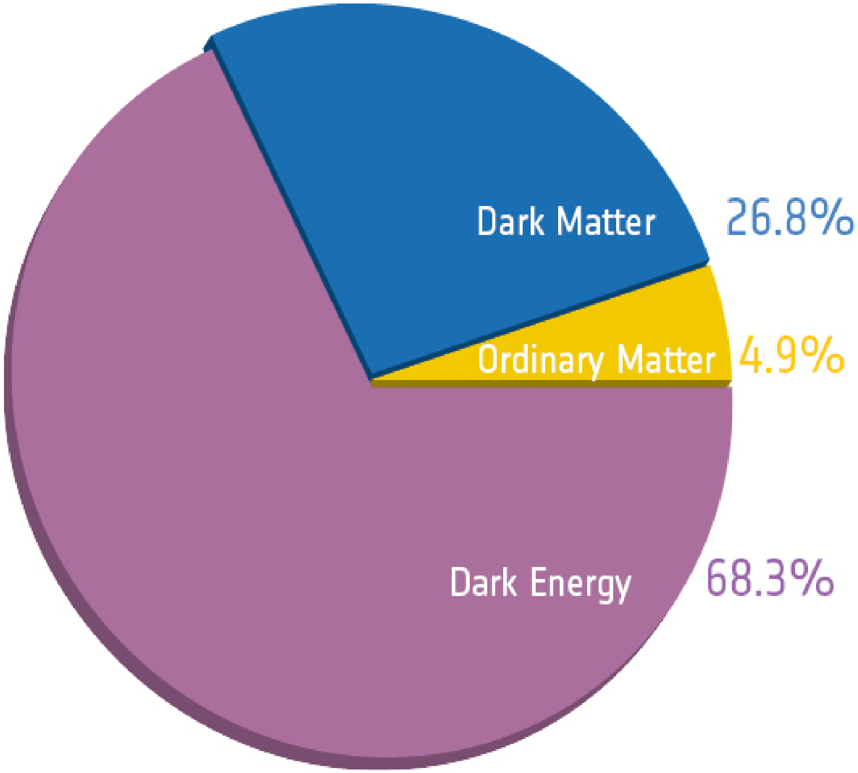


Galactic South

Comological parameters base-model results

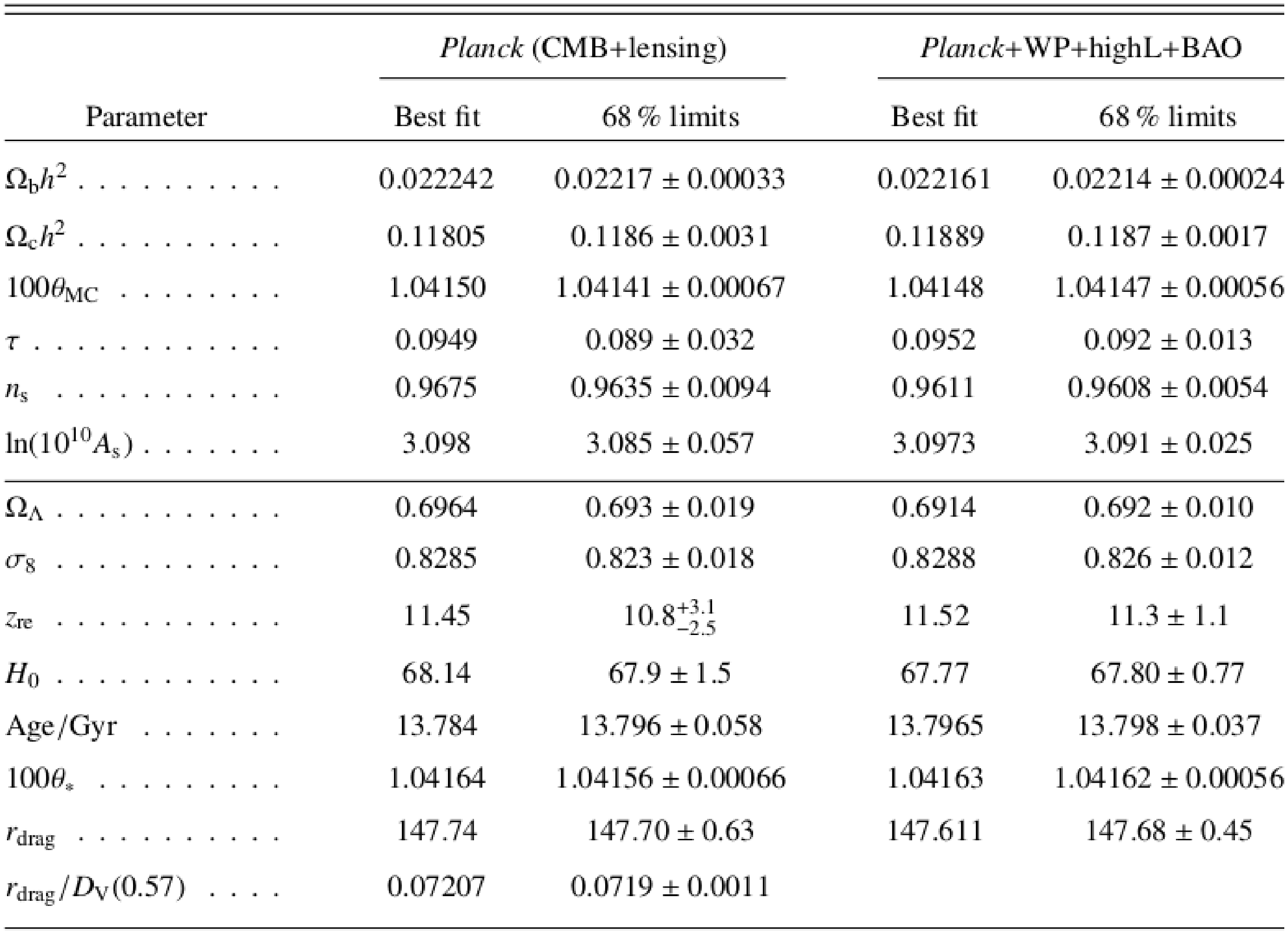


Before Planck



After Planck

Comological parameters base-model results



		Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
	Parameter	Best fit	68 % limits	Best fit	68 % limits
baryon density	$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
CDM density	$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
sound horizon (rad)	$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
reionization opacity	τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
Primordial spectrum {	n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
	$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
	Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
	σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
	z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
	H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
	Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
	$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
	r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
	$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Assumed Curvature: 0

Comological parameters base-model results

baryon density

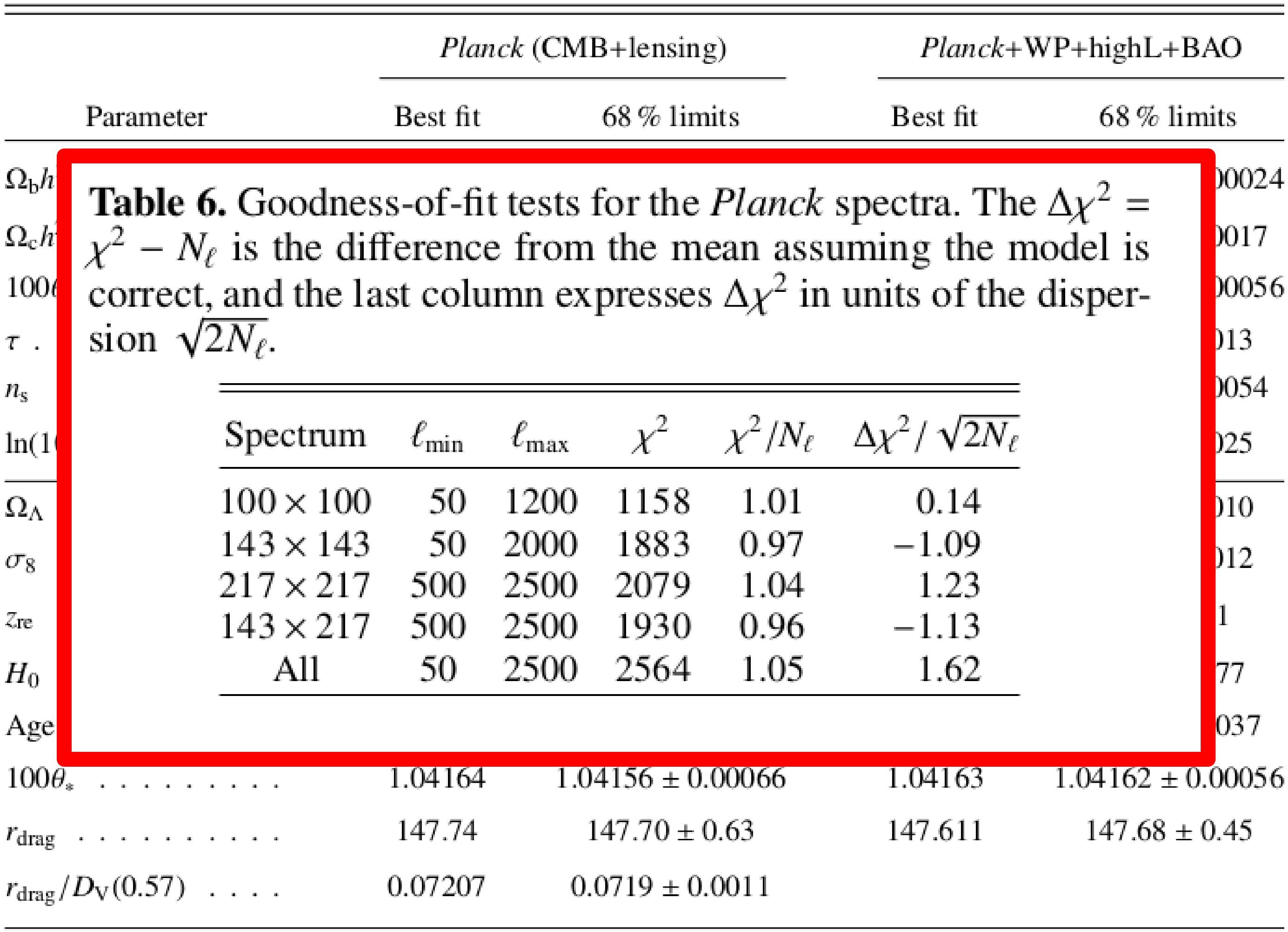
CDM density

sound horizon (rad)

reionization opacity

Primordial spectrum {

Assumed Curvature: 0



Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h$				0024
$\Omega_c h$				017
100				0056
τ .				13
n_s				054
ln(1				25
Ω_Λ				10
σ_8				12
z_{re}				1
H_0				77
Age				037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Table 6. Goodness-of-fit tests for the *Planck* spectra. The $\Delta\chi^2 = \chi^2 - N_\ell$ is the difference from the mean assuming the model is correct, and the last column expresses $\Delta\chi^2$ in units of the dispersion $\sqrt{2N_\ell}$.

Spectrum	ℓ_{min}	ℓ_{max}	χ^2	χ^2/N_ℓ	$\Delta\chi^2/\sqrt{2N_\ell}$
100×100	50	1200	1158	1.01	0.14
143×143	50	2000	1883	0.97	−1.09
217×217	500	2500	2079	1.04	1.23
143×217	500	2500	1930	0.96	−1.13
All	50	2500	2564	1.05	1.62

Comological parameters
base-model results

baryon density

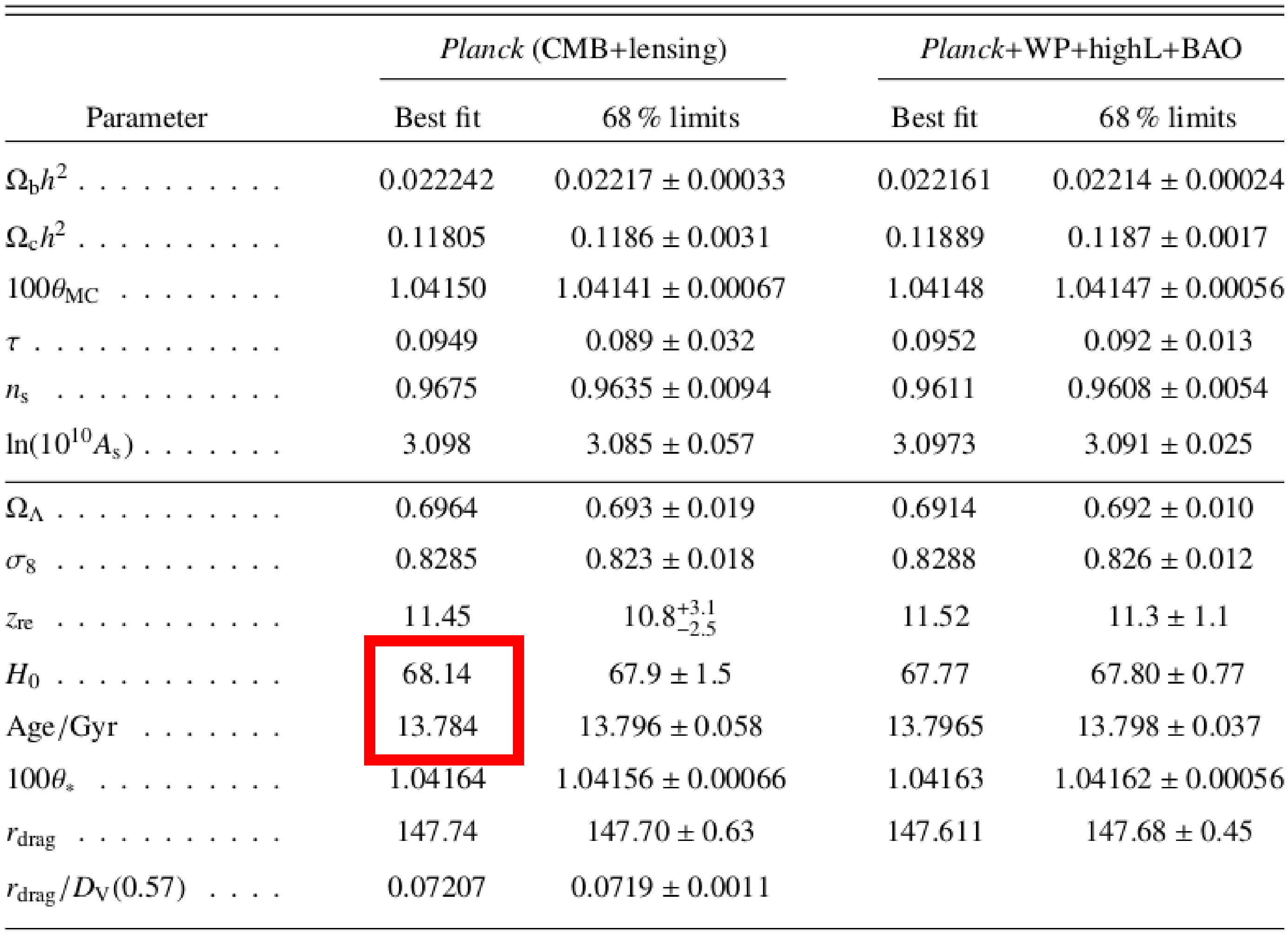
CDM density

sound horizon (rad)

reionization opacity

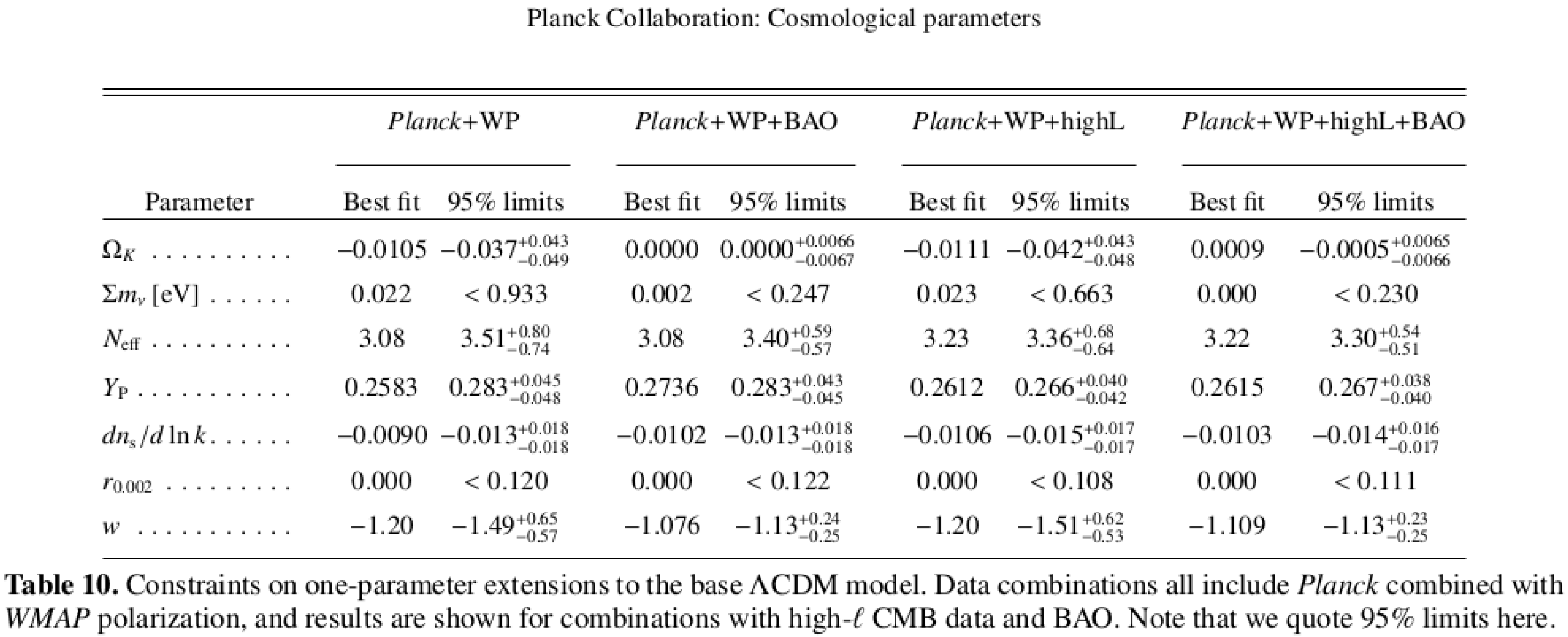
Primordial spectrum {

Assumed Curvature: 0



Parameter	*Planck* (CMB+lensing)		*Planck*+WP+highL+BAO	
	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Extensions of base model



Planck Collaboration: Cosmological parameters

	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\rm s}/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

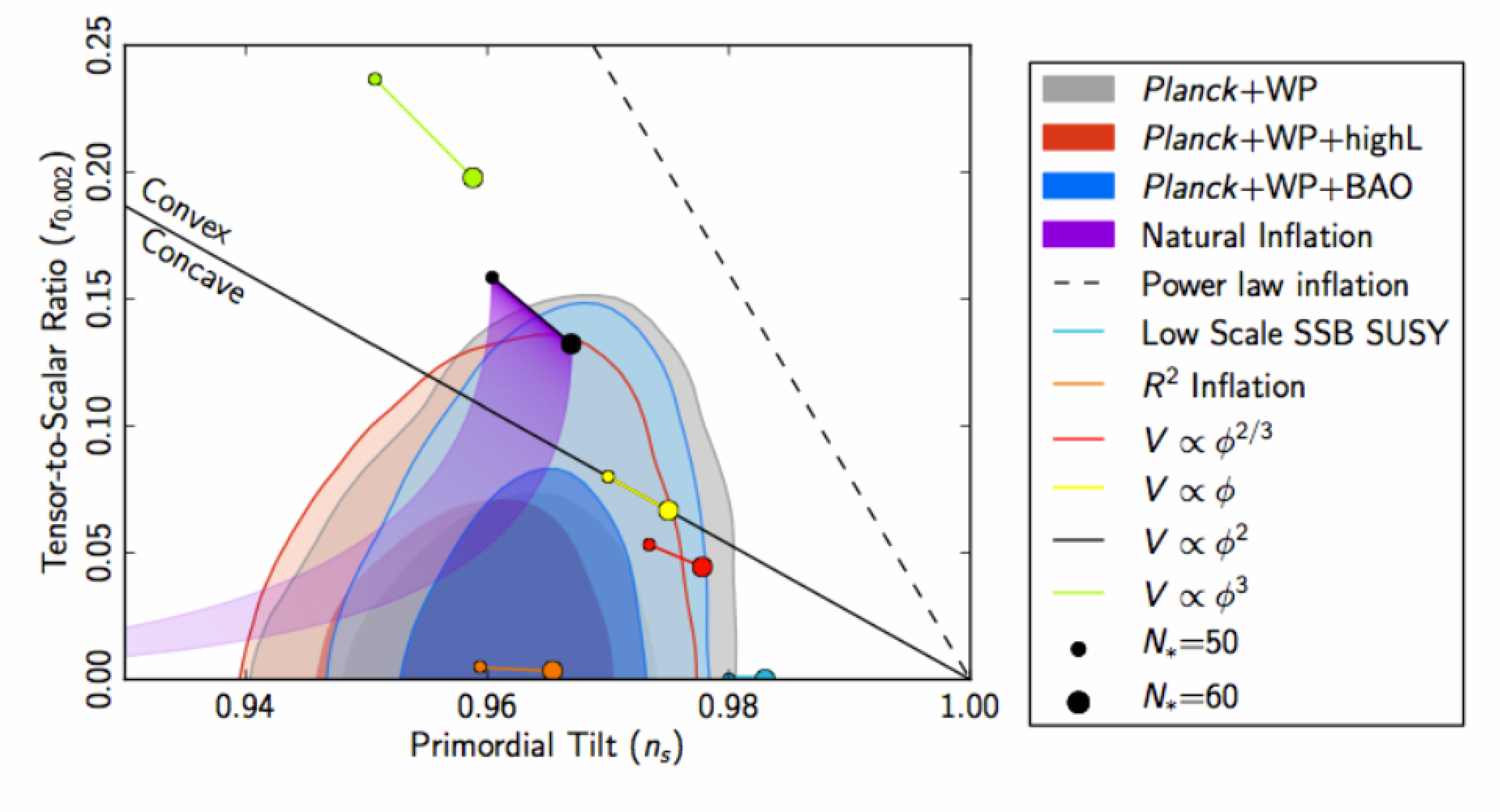
Table 10. Constraints on one-parameter extensions to the base ΛCDM model. Data combinations all include *Planck* combined with *WMAP* polarization, and results are shown for combinations with high-ℓ CMB data and BAO. Note that we quote 95% limits here.

implications

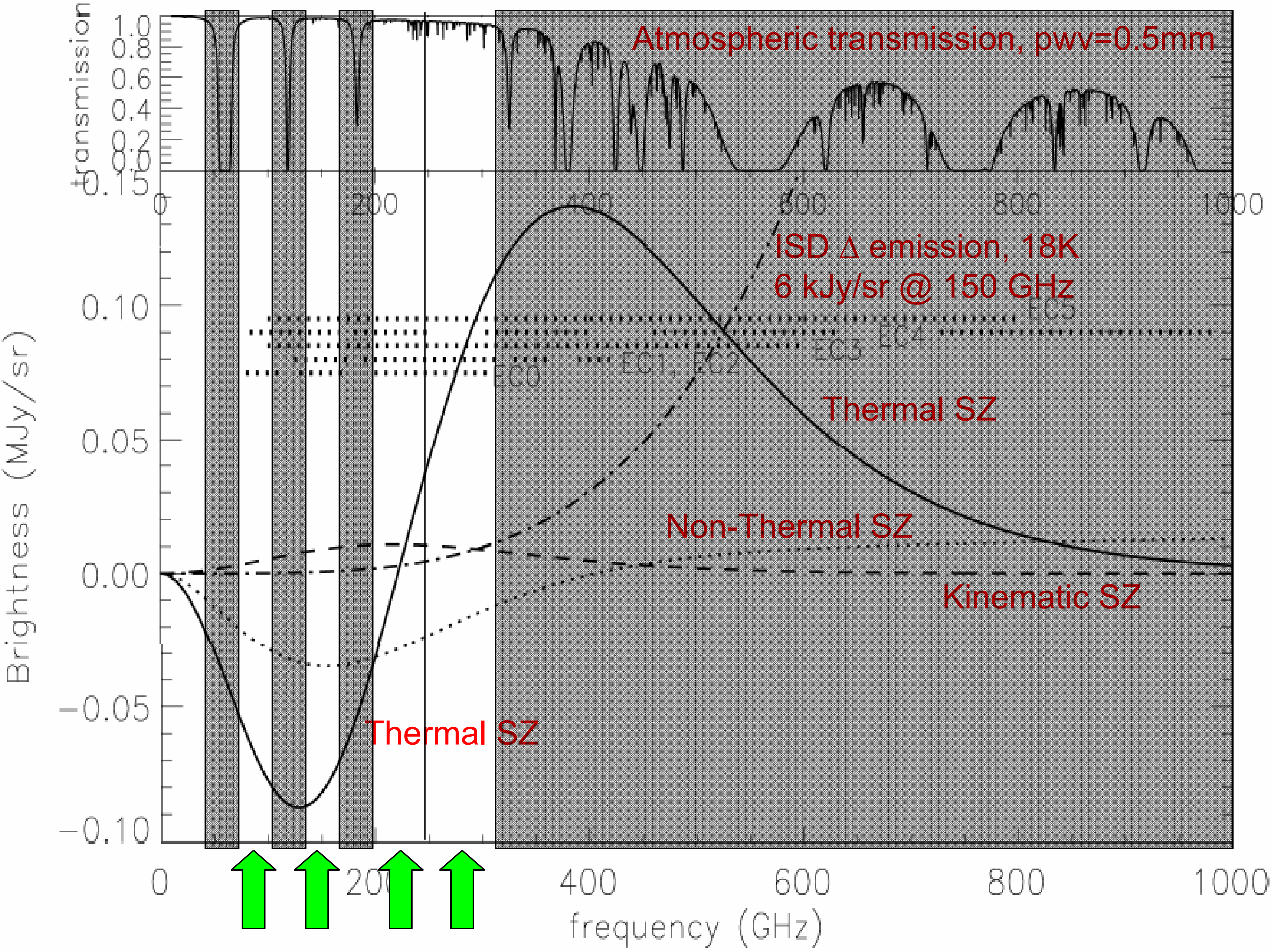
Planck+WP+highL+BAO

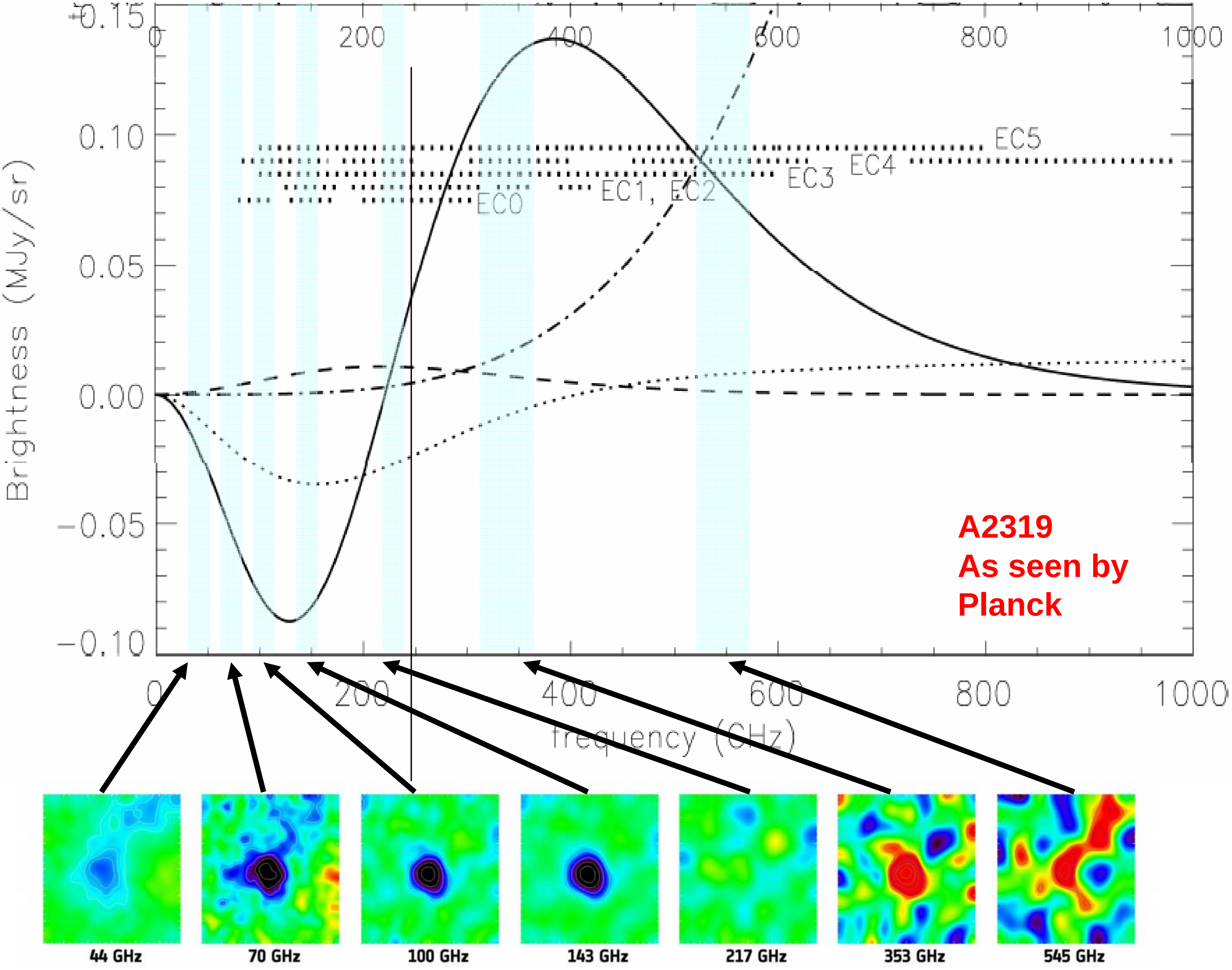
- sound horizon is determined by the position of the 7 peaks, and now measured at 0.05% precision → 1.04147 ± 0.00056
- n_s: exact scale invariance of the primordial fluctuations is ruled out, at more than 7σ (as predicted by base inflation models) → 0.9608 ± 0.0054
- 95%CL upper limit on sum of neutrino masses → $\sum m_\nu < 0.23\,\mathrm{eV}$
- 3 neutrinos species favored by Planck → $N_{\mathrm{eff}} = 3.30^{+0.54}_{-0.51}$
- no evidence for dynamical dark energy

some inflation models are excluded



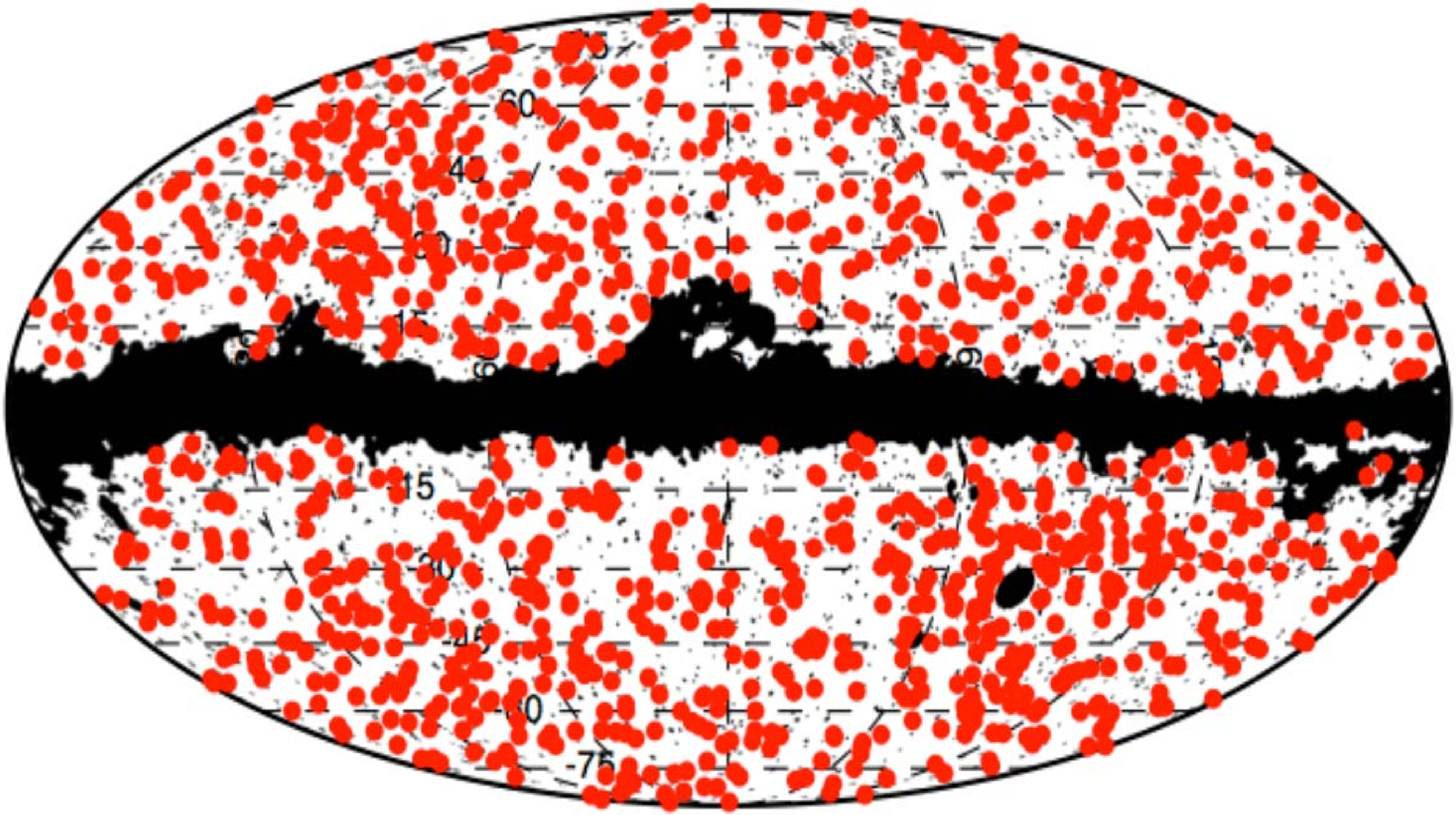
best ground-based photometers: 4 bands



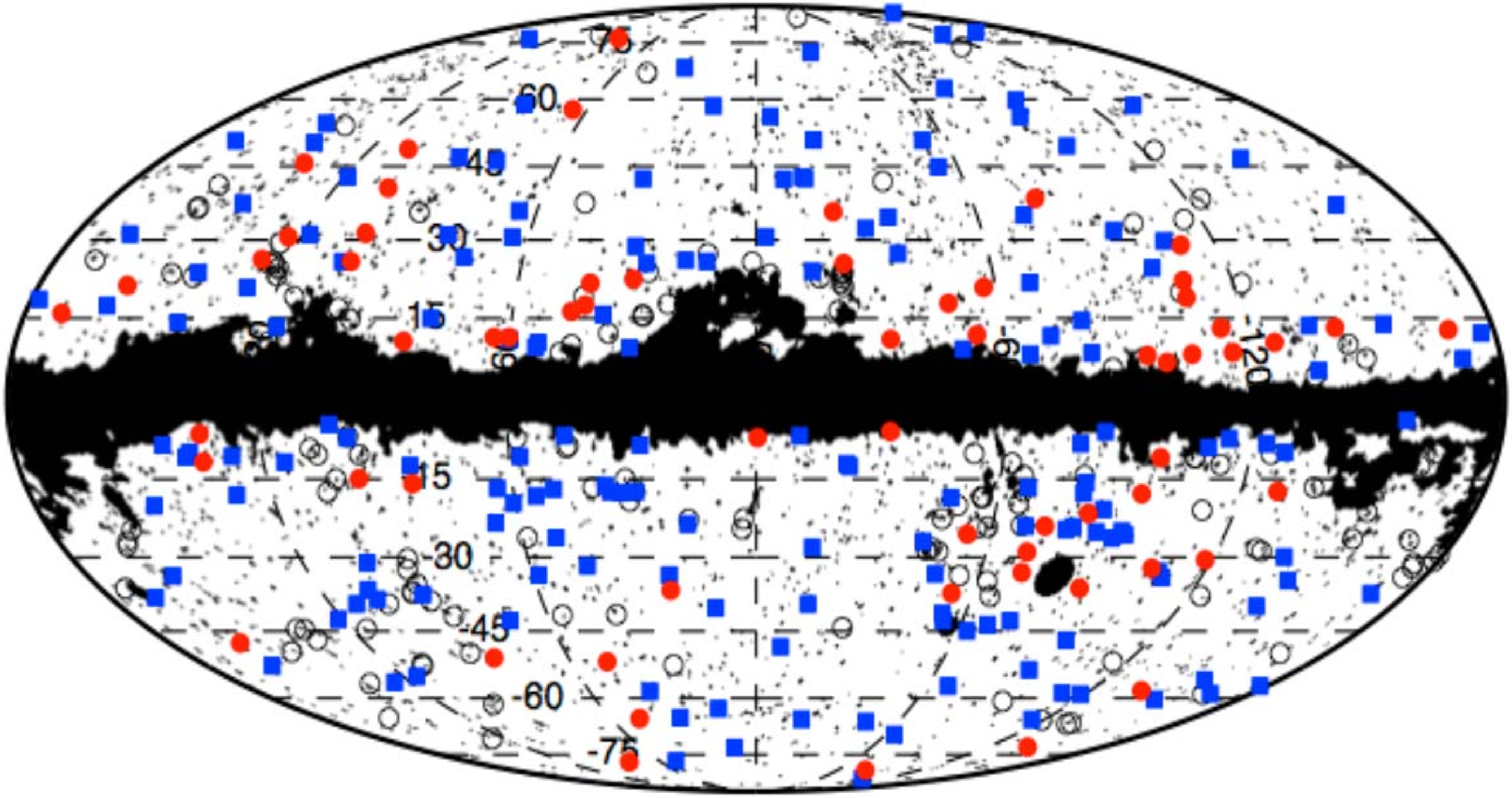


A2319
As seen by
Planck

1227 SZ clusters

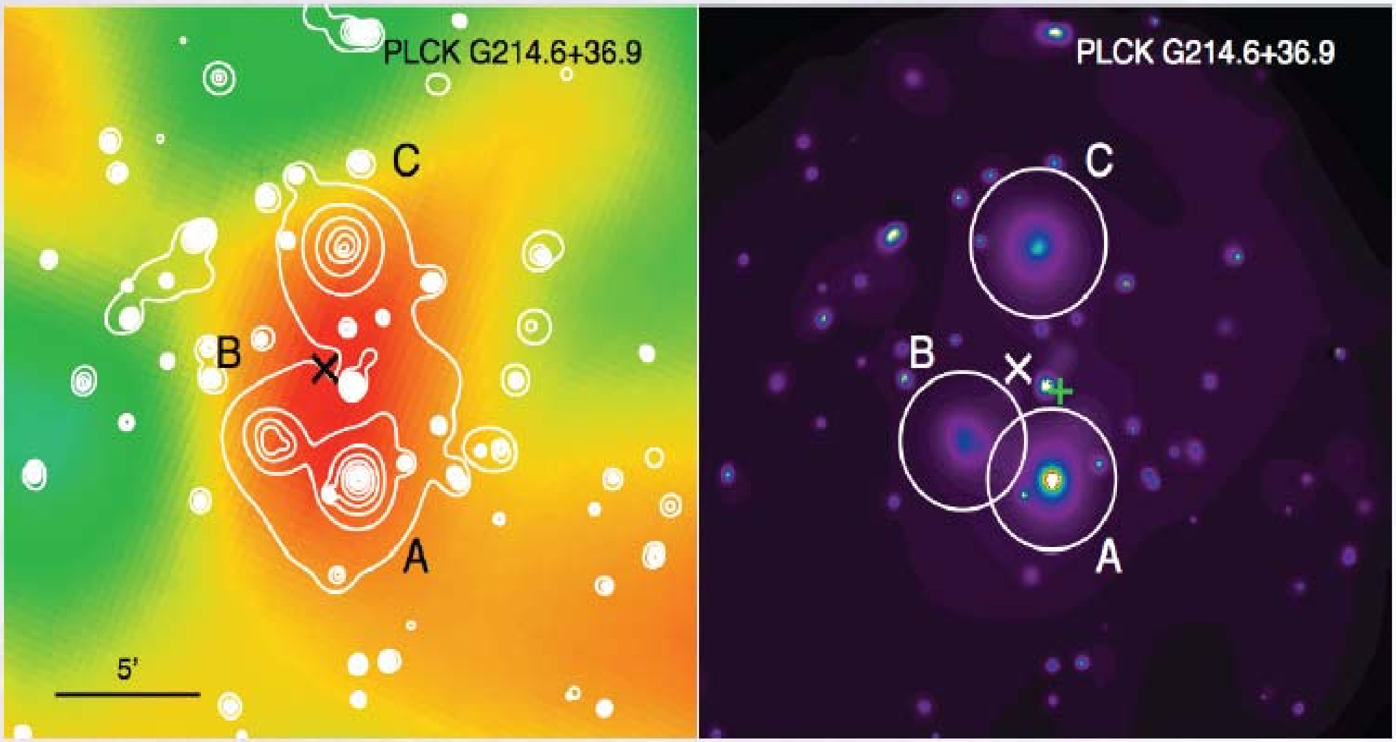


337 brand-new clusters



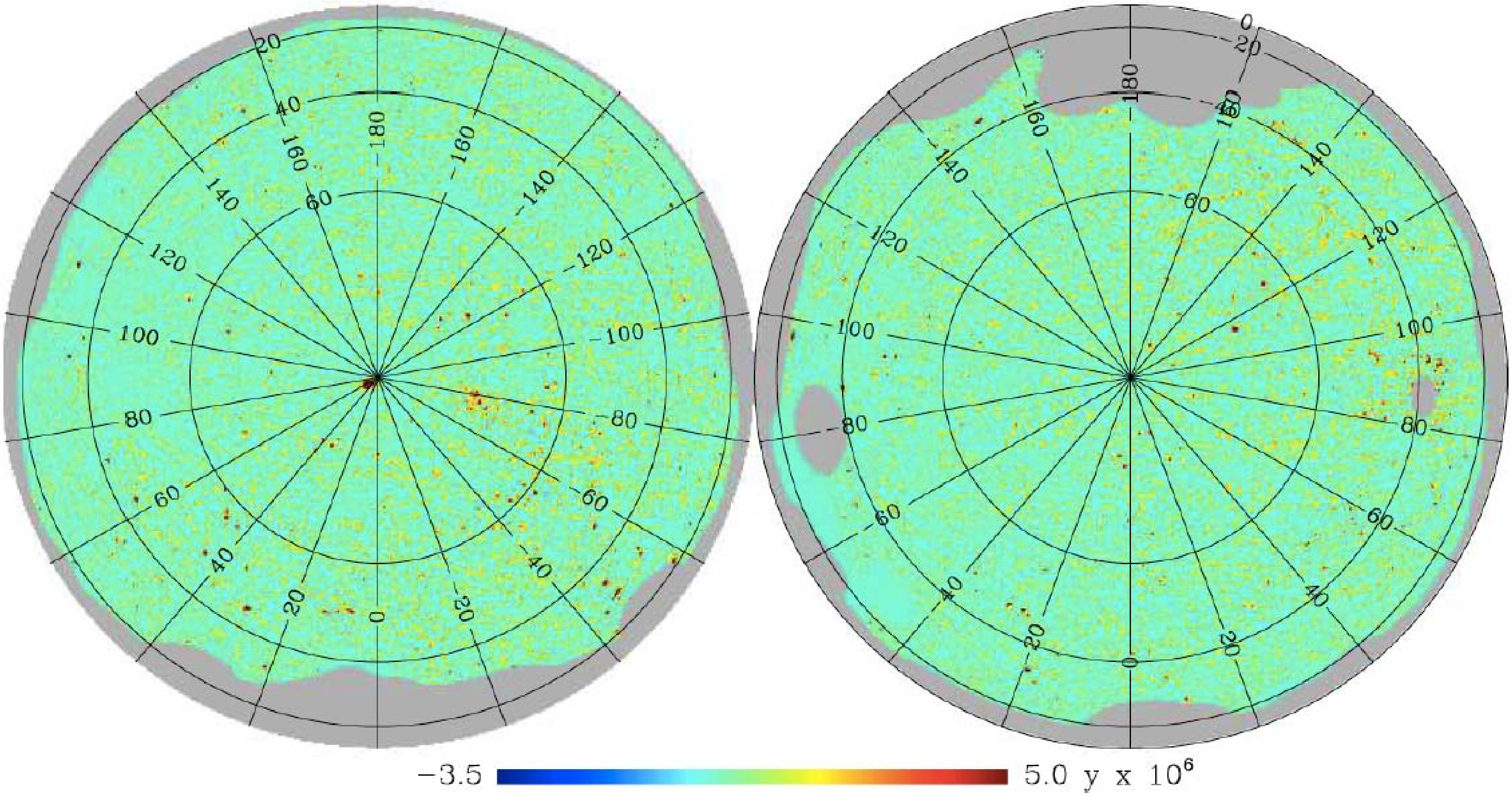
All-sky Sunyaev-Zeldovich clusters

Multiple Systems

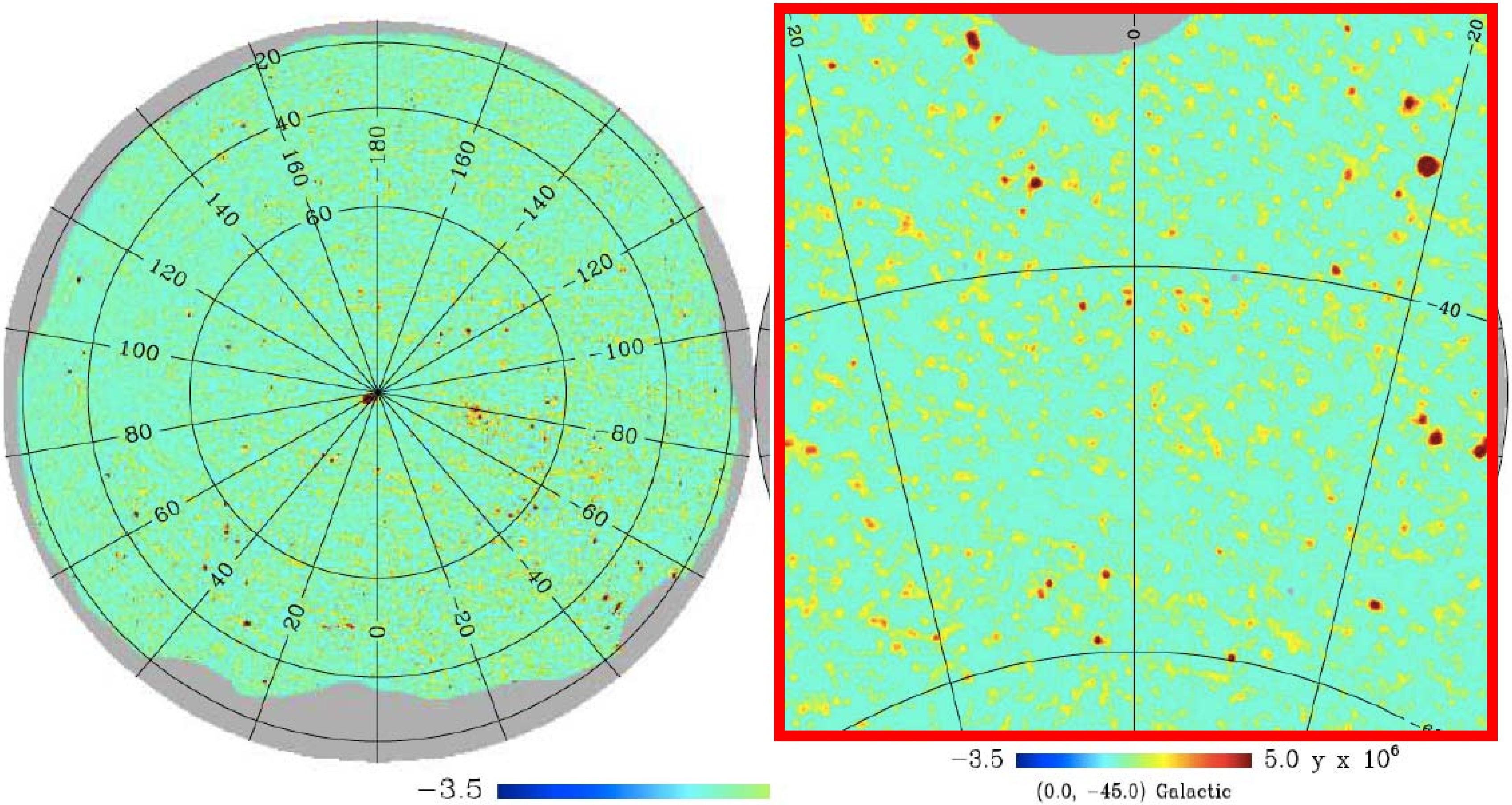


Example of the triple system PLCK G214.6+37.0. *Planck* Y_{SZ} *map (left)* with contours from the *XMM-Newton* wavelet filtered [0.3 – 2] keV image (right) overlaid in white. Extended components found in the *XMM-Newton* image are marked with letters. The circles in each *XMM-Newton* image denote the estimated R_{500} radius for each component.

Full-sky map of diffuse SZe (hot baryons)

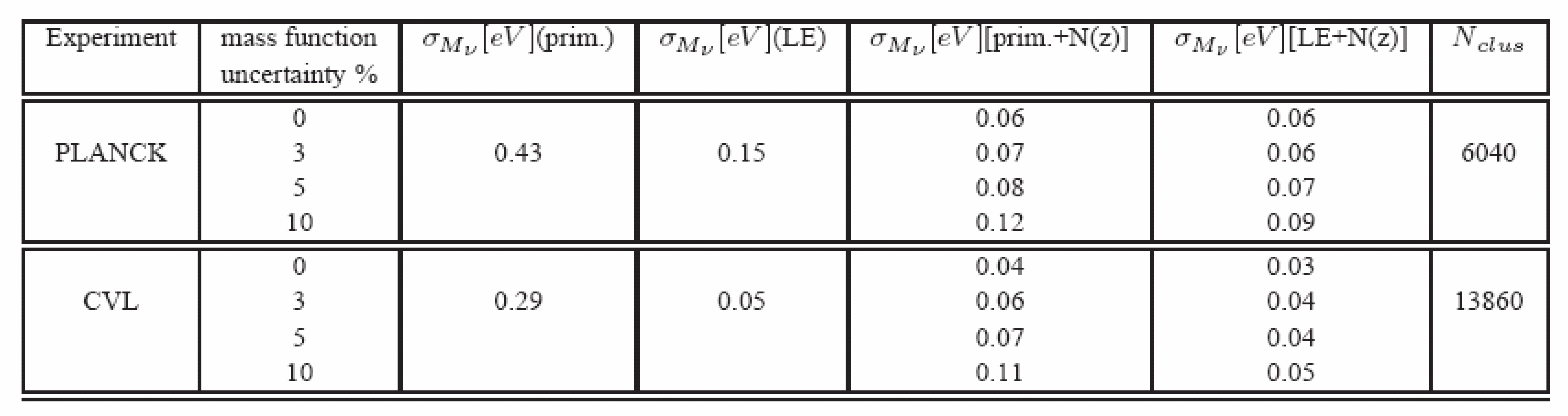


Full-sky map of diffuse SZe (hot baryons)

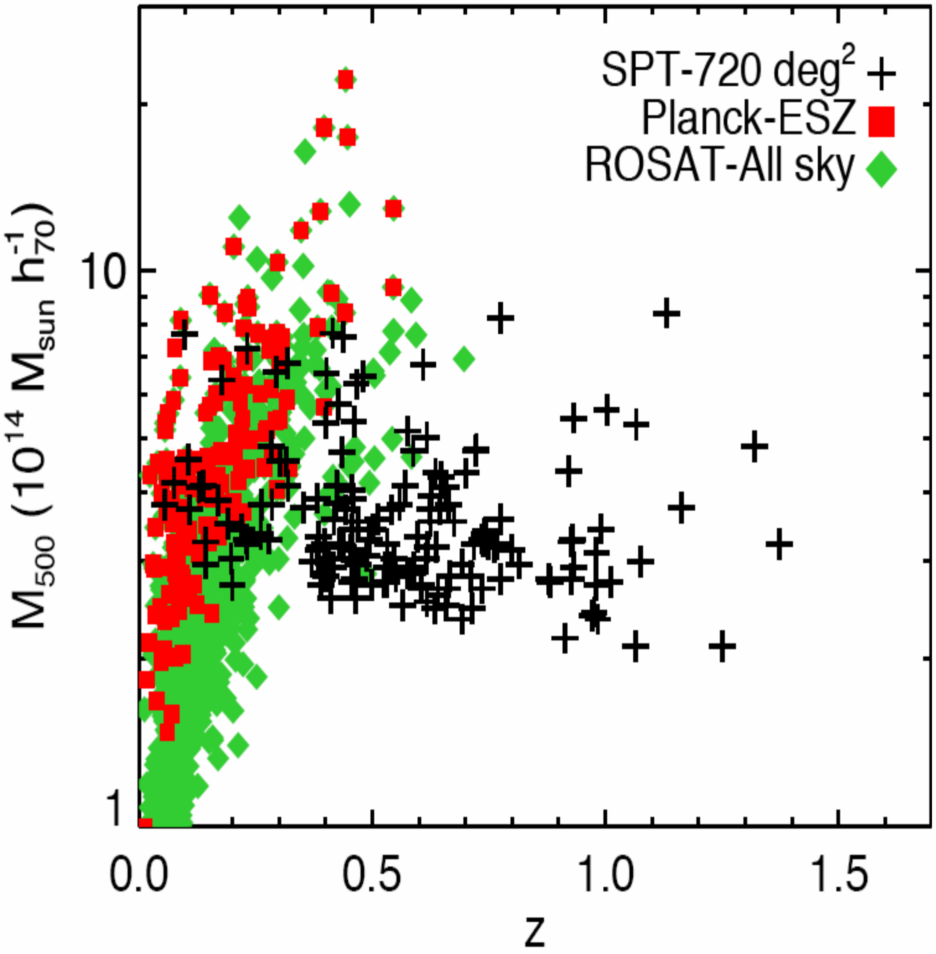


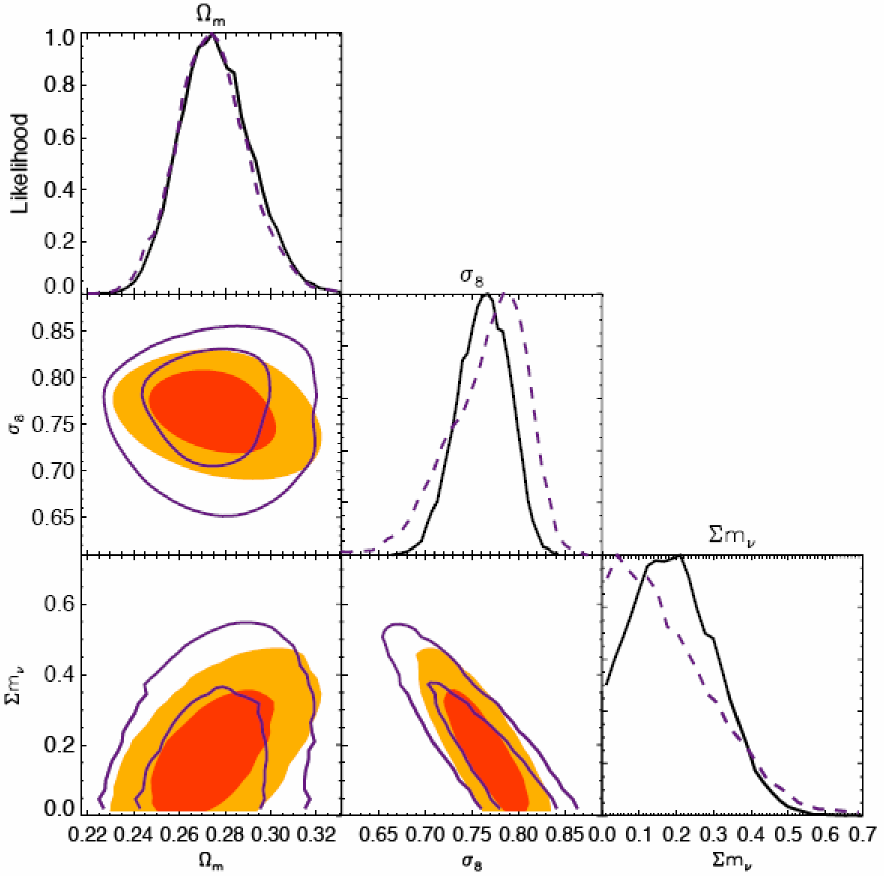
SZ effect and ν-mass

- Via SZ observations it is possible to obtain Cluster number counts N(z) up to large distances, with small bias.
- N(z) depends strongly on the matter spectrum, and in turn on the ν-mass.
- Shimon et al. astro-ph/1201.1803 have shown that, while lensed CMB measurements from Planck can reach a sensitivity of 0.15 eV, using the SZ cluster counts from Planck one can reach 0.06 eV.
- Future cosmic variance limited surveys can reach 0.03 eV. However, the mass function of clusters has to be known to the 1% level. This should be reacheable in the future.



Experiment	mass function uncertainty %	$\sigma_{M_\nu}[eV]$(prim.)	$\sigma_{M_\nu}[eV]$(LE)	$\sigma_{M_\nu}[eV]$[prim.+N(z)]	$\sigma_{M_\nu}[eV]$[LE+N(z)]	N_{clus}
PLANCK	0 3 5 10	0.43	0.15	0.06 0.07 0.08 0.12	0.06 0.06 0.07 0.09	6040
CVL	0 3 5 10	0.29	0.05	0.04 0.06 0.07 0.11	0.03 0.04 0.04 0.05	13860





SPT SZ survey (550 sq.deg.)
134 new clusters *discovered* with the SZ effect
(confirmed by optical and IR follow ups).
Reichart et al. astro-ph/1203.5775

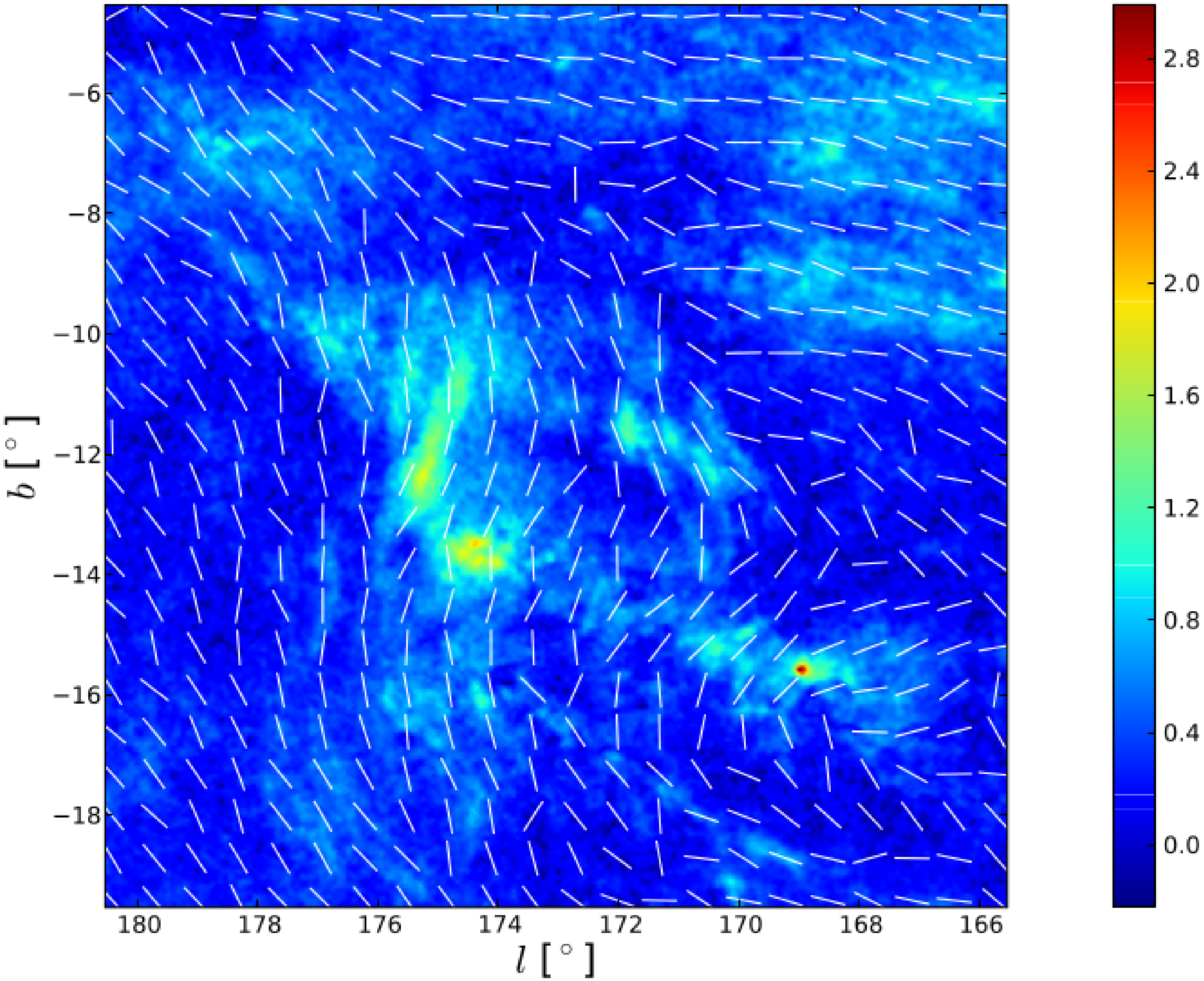
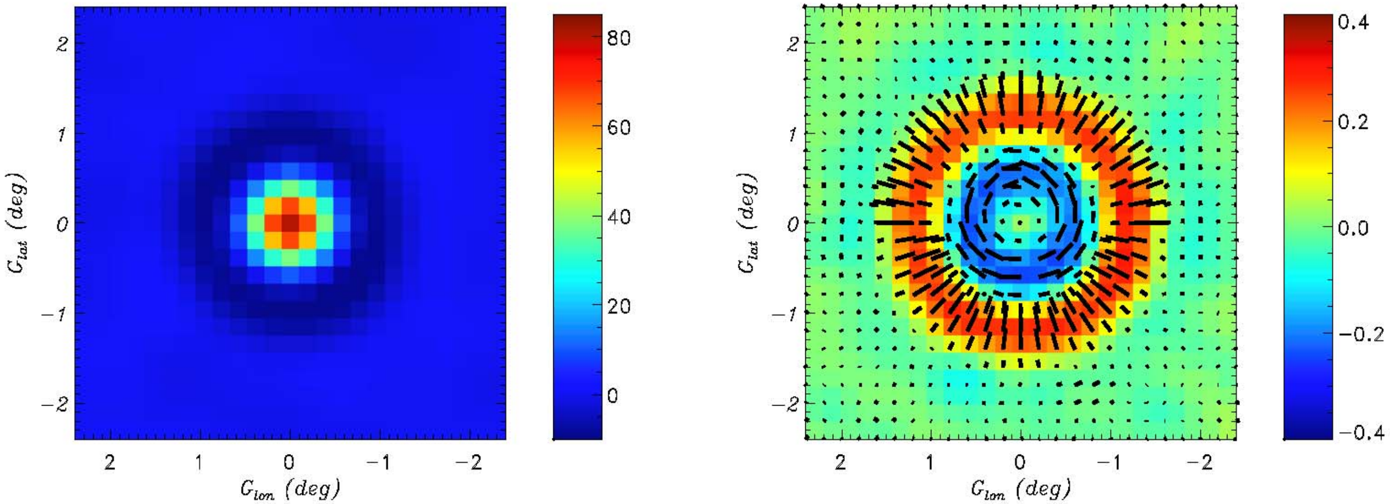


Fig. 24. Polarised intensity at 353 GHz (in mK$_{CMB}$) and polarization orientation indicated as segments of uniform length, in the Taurus region.

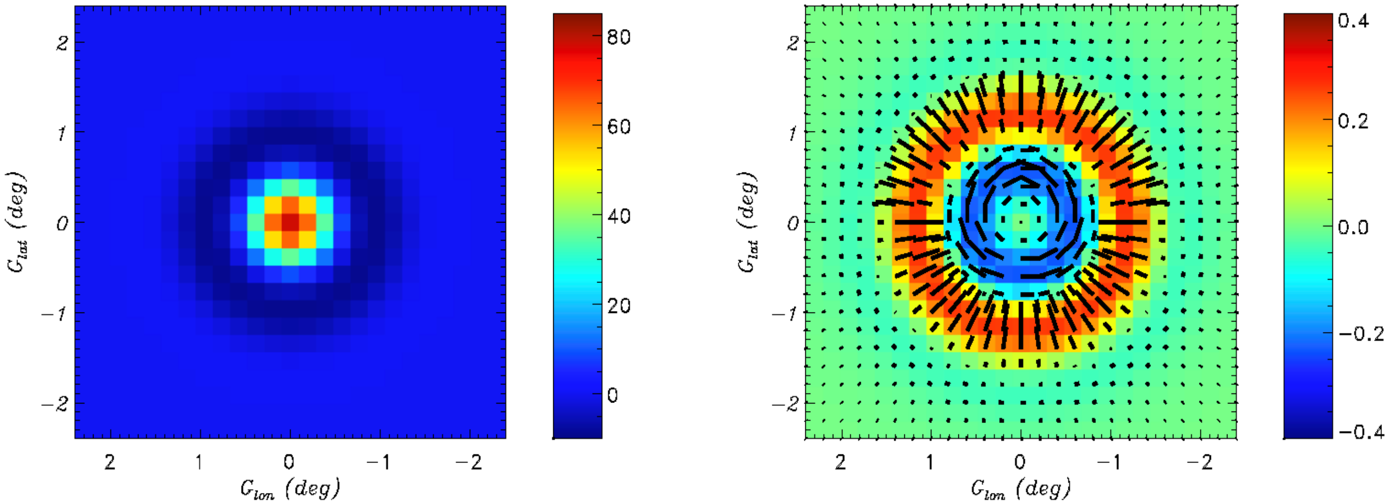
Stacking CMB polarization patterns



Intensity (hot spots)

Q$_r$ (hot spots)

Planck



Model

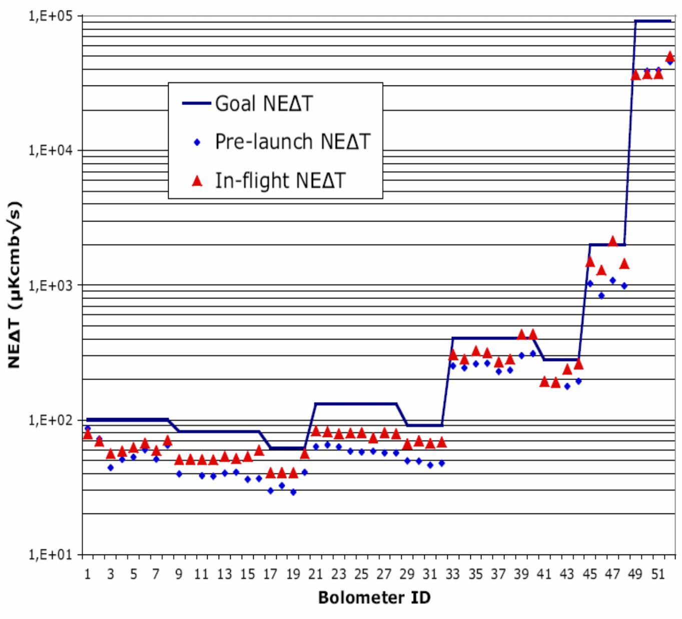
Much more in the papers …
…. and much more to come :

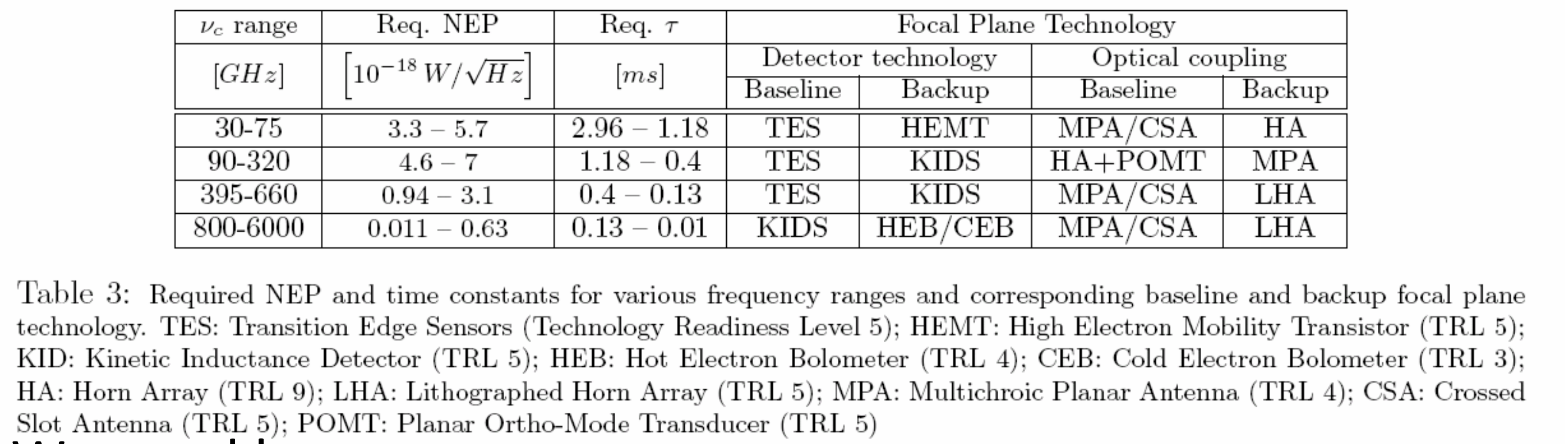
Full polarization analysis

Mid 2014

Bolometer performance in space

- Heritage from Planck, Herschel (L2): High sensitivity – the limit is CR hits.
- Survey sensitivity improvement obtained mainly by multiplication of the number of detectors (photon noise limited bolometers, with background = astro + 10K mirror)
- The sensitivity requirement of ***PRISM*** is not terribly stringent, and technologues are available :



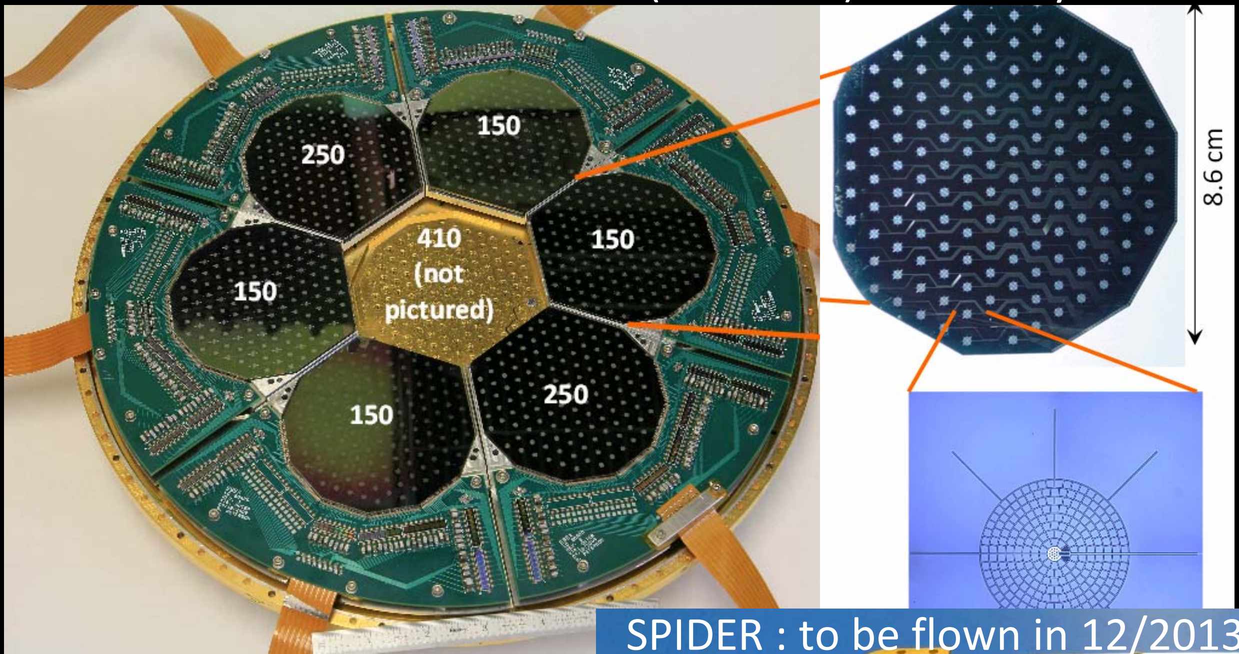


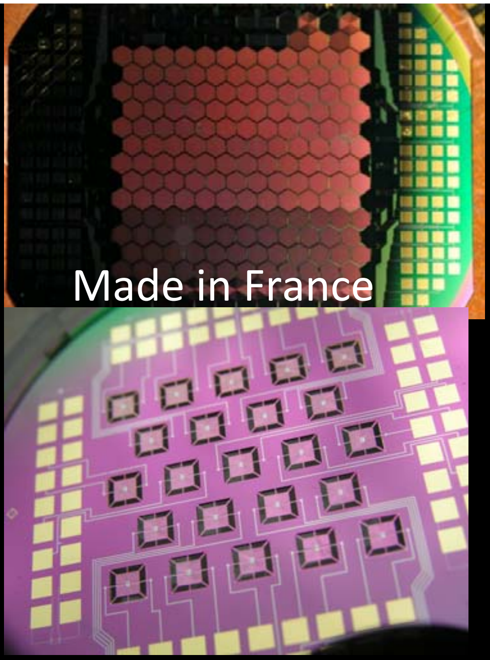
ν_c range	Req. NEP	Req. τ	Focal Plane Technology			
$[GHz]$	$\left[10^{-18}\, W/\sqrt{Hz}\right]$	$[ms]$	Detector technology		Optical coupling	
			Baseline	Backup	Baseline	Backup
30-75	3.3 – 5.7	2.96 – 1.18	TES	HEMT	MPA/CSA	HA
90-320	4.6 – 7	1.18 – 0.4	TES	KIDS	HA+POMT	MPA
395-660	0.94 – 3.1	0.4 – 0.13	TES	KIDS	MPA/CSA	LHA
800-6000	0.011 – 0.63	0.13 – 0.01	KIDS	HEB/CEB	MPA/CSA	LHA

Table 3: Required NEP and time constants for various frequency ranges and corresponding baseline and backup focal plane technology. TES: Transition Edge Sensors (Technology Readiness Level 5); HEMT: High Electron Mobility Transistor (TRL 5); KID: Kinetic Inductance Detector (TRL 5); HEB: Hot Electron Bolometer (TRL 4); CEB: Cold Electron Bolometer (TRL 3); HA: Horn Array (TRL 9); LHA: Lithographed Horn Array (TRL 5); MPA: Multichroic Planar Antenna (TRL 4); CSA: Crossed Slot Antenna (TRL 5); POMT: Planar Ortho-Mode Transducer (TRL 5)

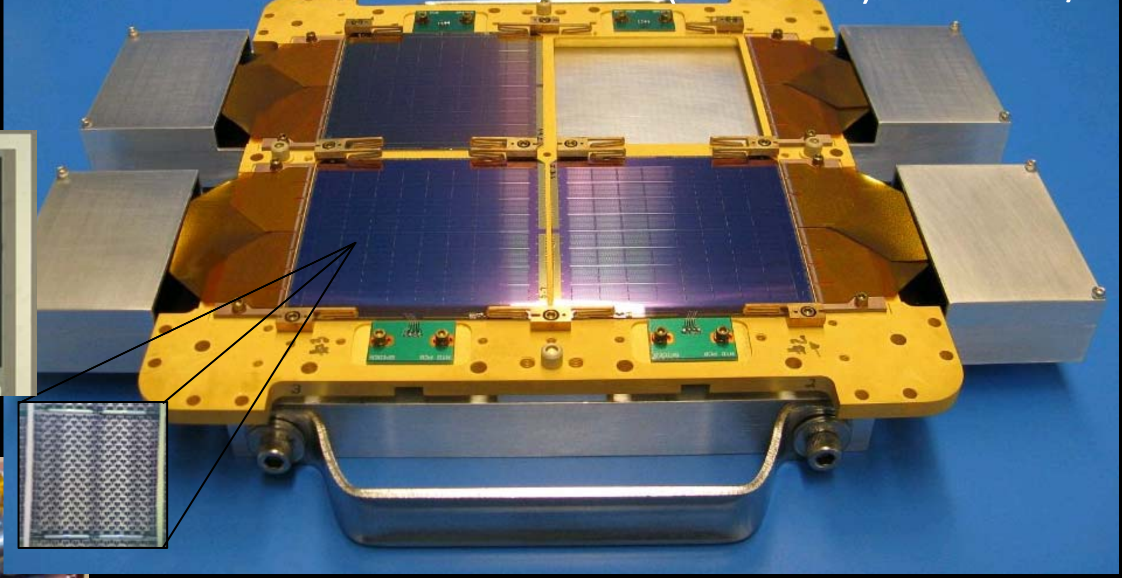
- We need large arrays.

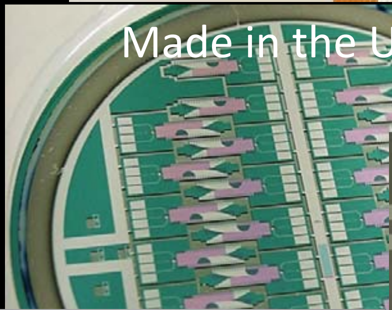
EBEX: flown in 2012 (850+ bol.) – Berkeley




Made in France

SPIDER : to be flown in 12/2013 (2048 bol.) – Caltech/JPL




Made in the UK

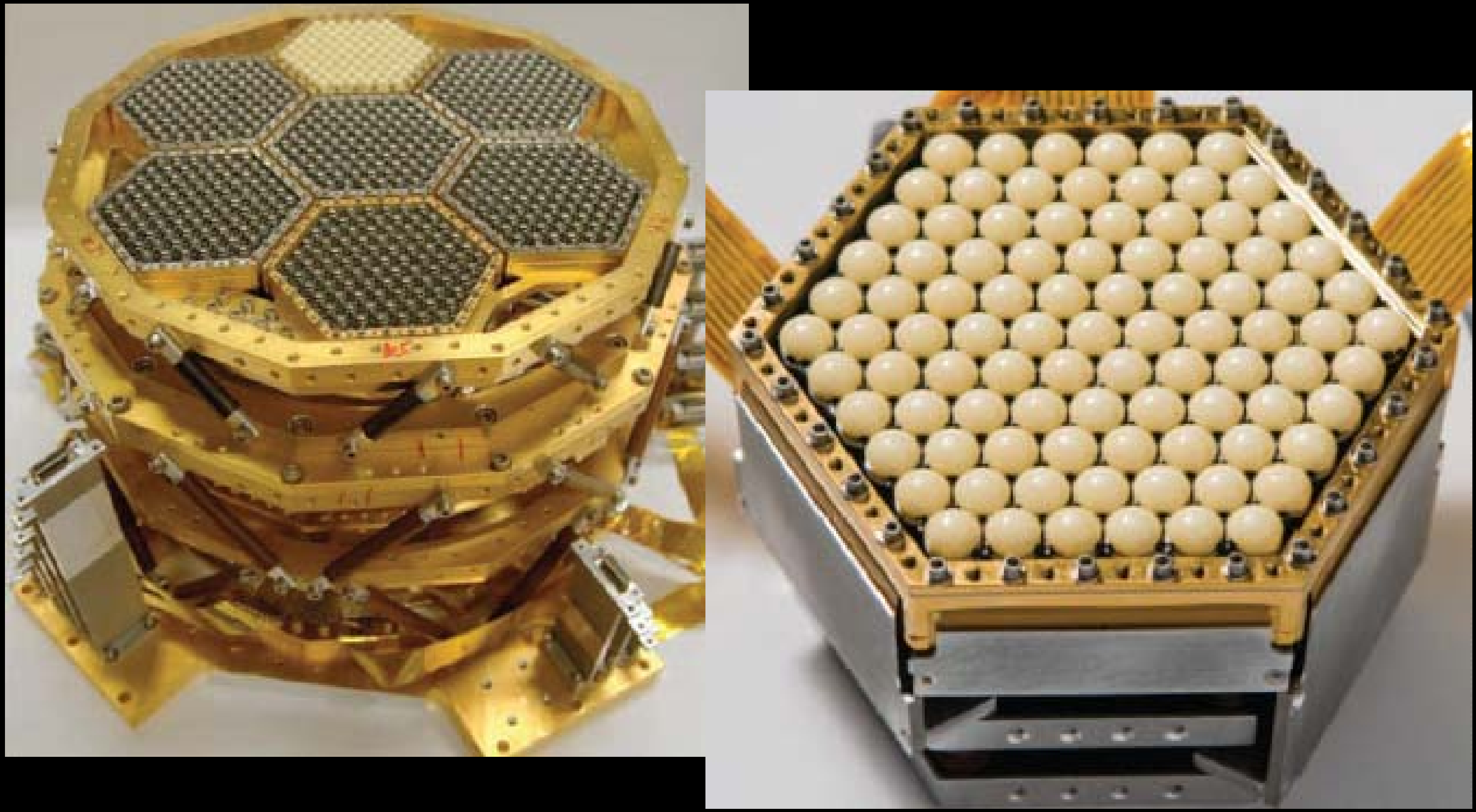
Made in The Netherlands


Made in Germany


Made in Italy

TES bolometer arrays : HUGE effort and great success. Now a mature technology.

The trend :

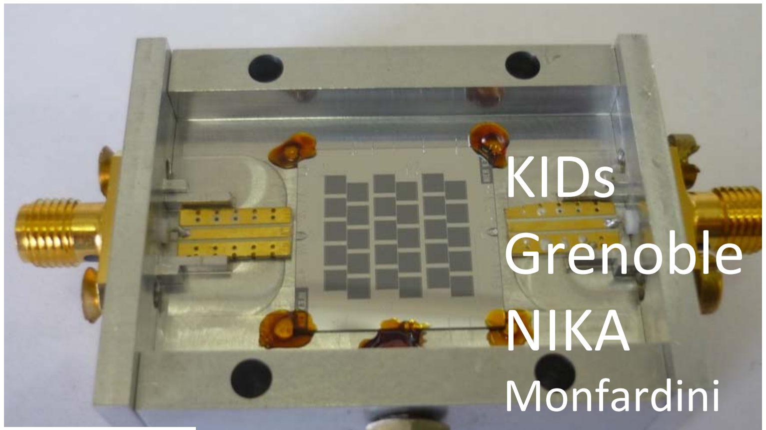


- Large arrays of multichroic pixels: 6000+ detectors for polarbear2, SPTpol, litebird …
- ESA ITT for compact focal planes (Maynooth)

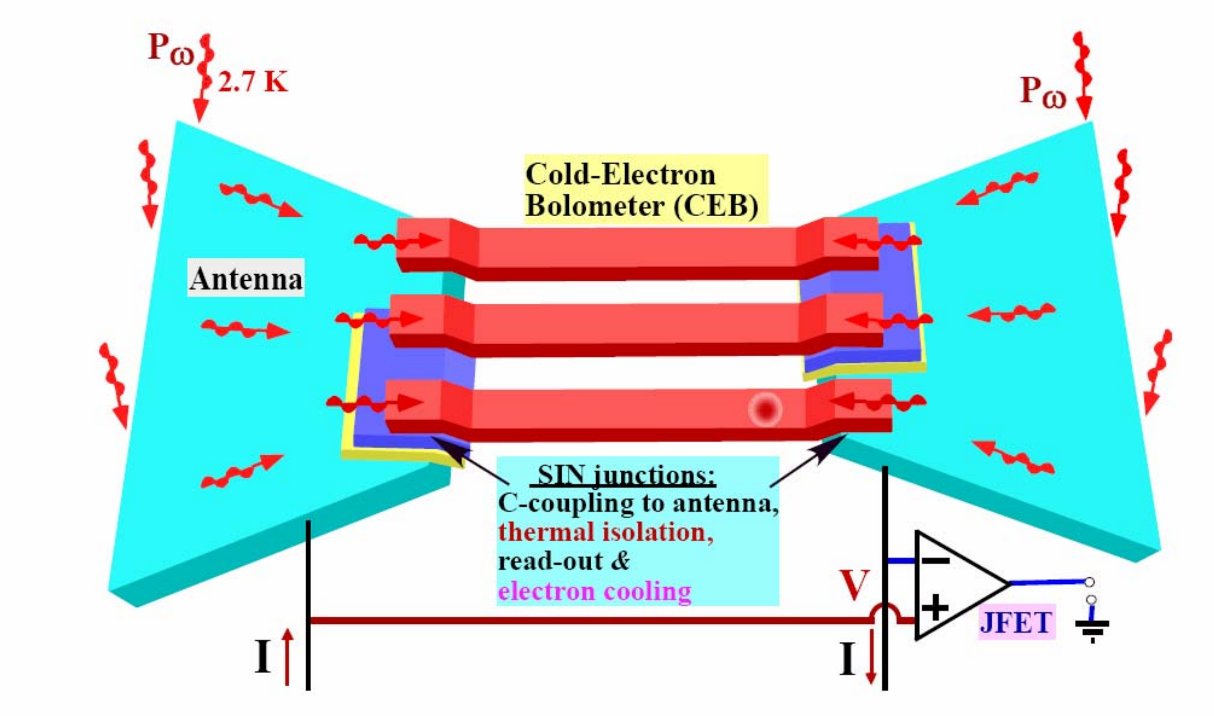
2)

Improving over TES bolometers ?

- KIDs & CEBs !
- KIDs made in Cardiff, Grenoble, Rome/TN etc.
- CEBs made in Chalmers



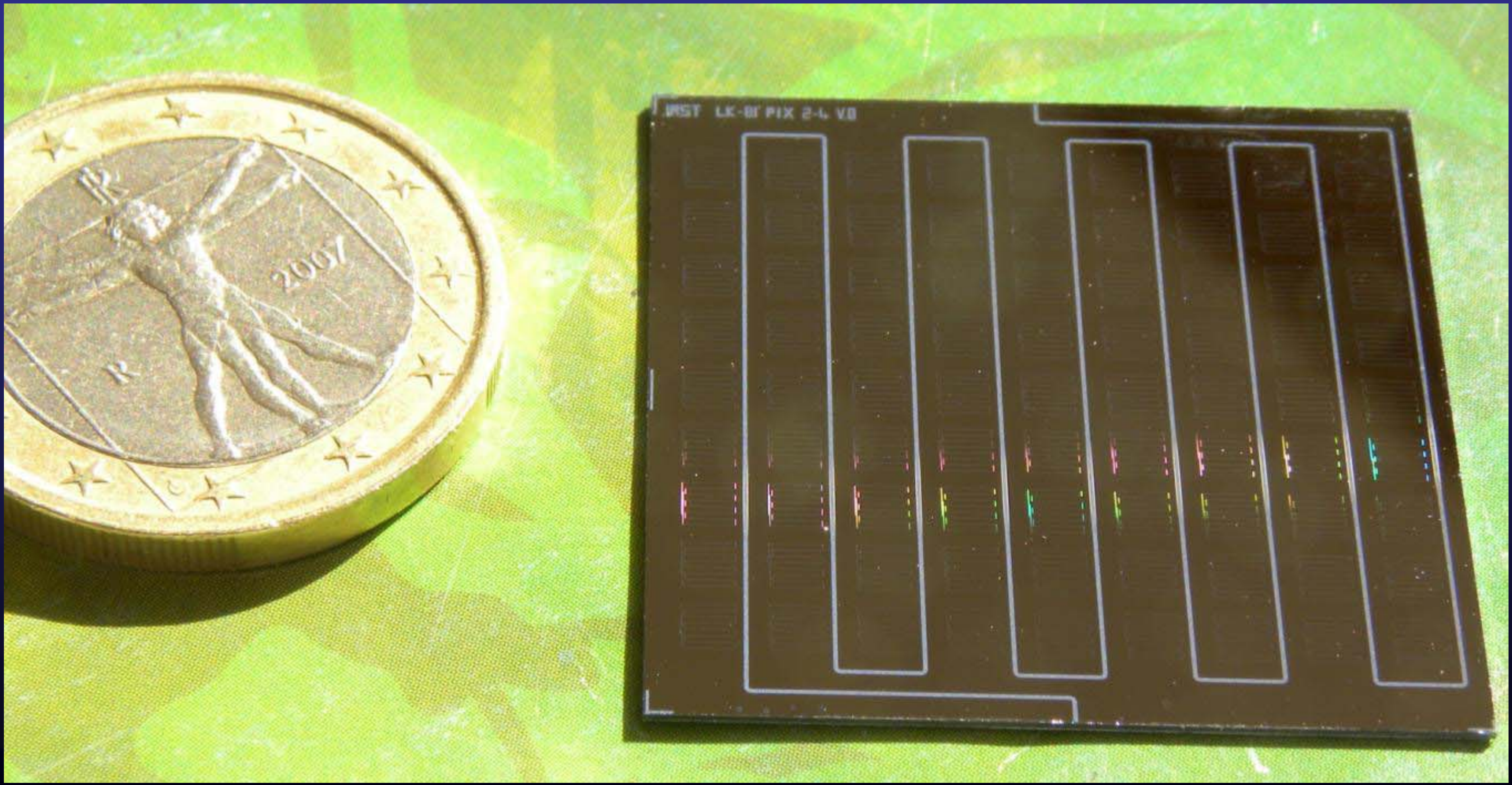
KIDs
Grenoble
NIKA
Monfardini
et al. 2011



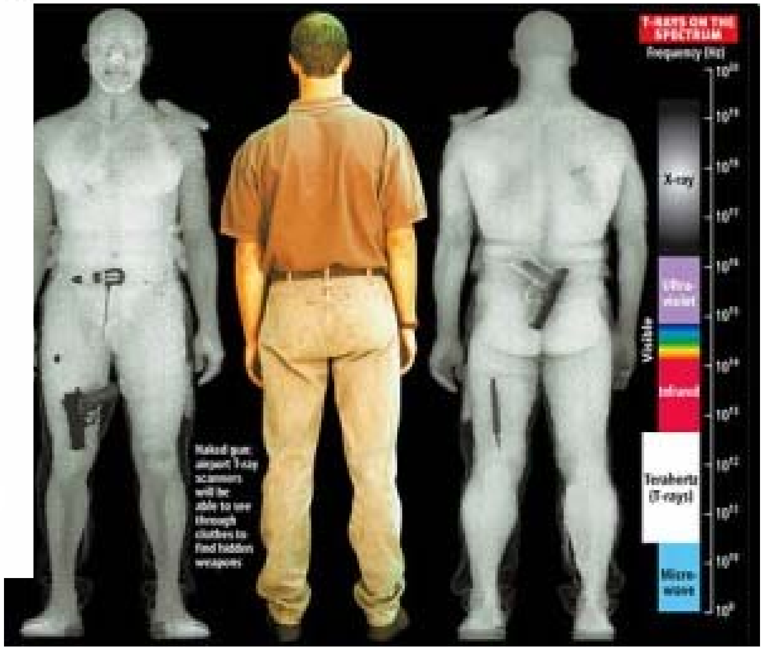
Very insensitive to CR hits (sensing electrons are confined in a sub-μm sized junction, and effectively decoupled from the lattice)
Kuzmin et al. 2010

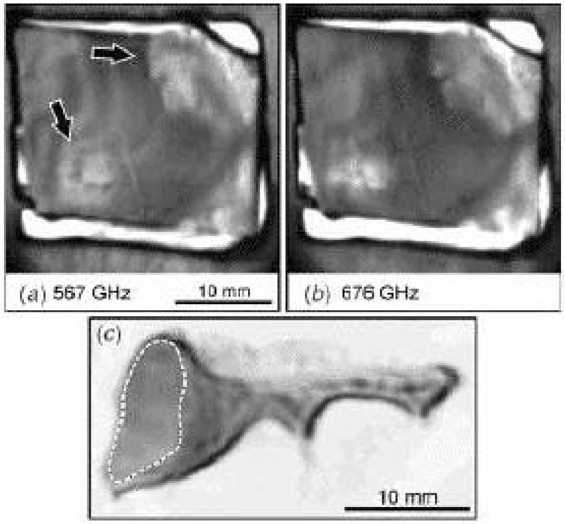
KIDs

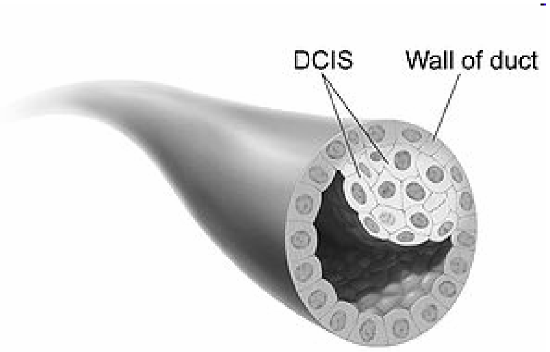
- You heard about the great results of the Grenoble group with kinetic inductance detectors at the IRAM dish (NIKA).
- However, CMB BLIP is not reached yet, and standard KIDs are very sensitive to CR hits.
- KIDs are easier than TES to build, at least in the ground based versions.
- Space-based version still to be developed, and significant added complexity.



KIDs array made in Italy (Calvo et al. 2010)

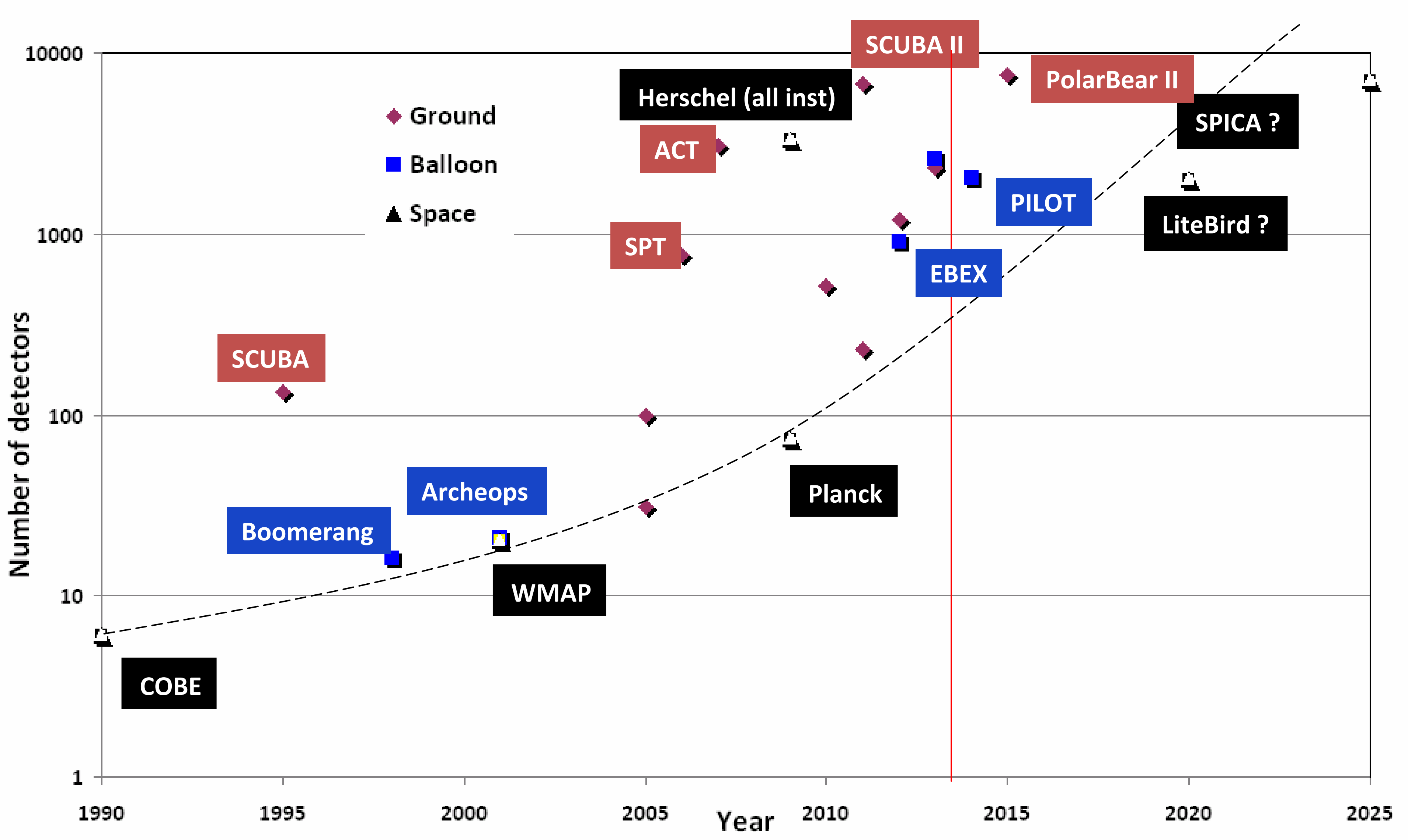






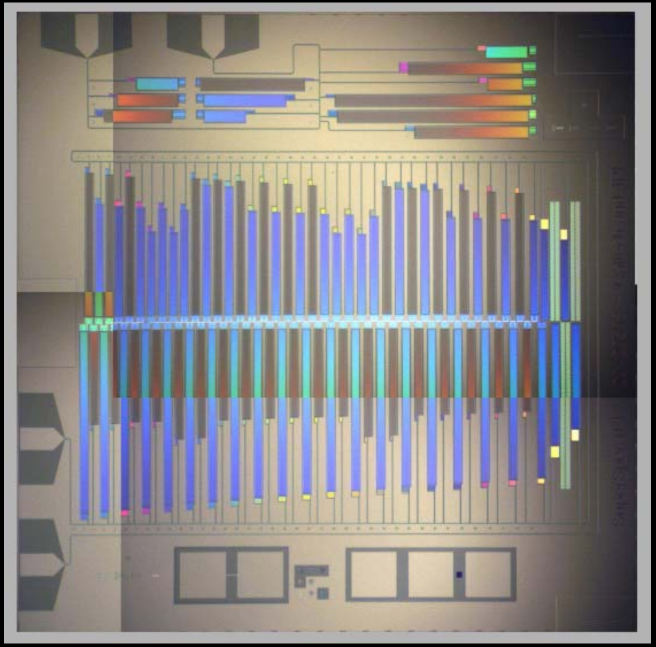
National Cancer Institute

Evolution of number of detectors in mm-wave / sub-mm projects

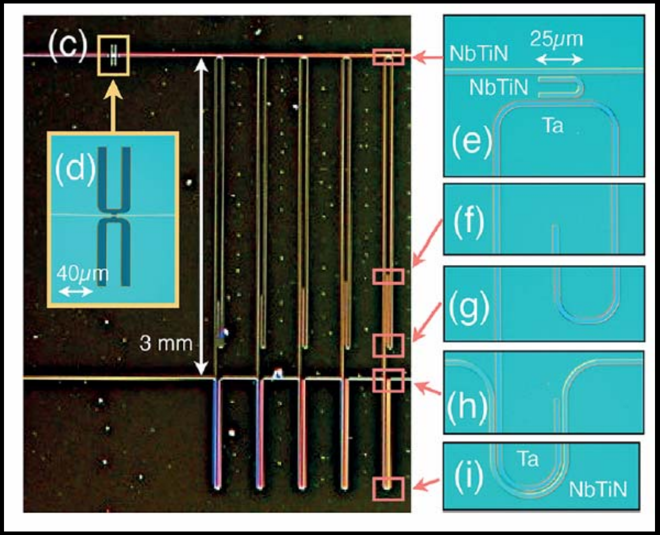


Lines monitors

- Need R=40 @ sub-mm
  - Monitor Galactic lines
  - Get redshifts from C+ line
- Either single pixels with narrow-band filters
- Or narrow-band channelizers
- or filter-bank on chip (Superspec, Deshima, and similar)
- Very promising !



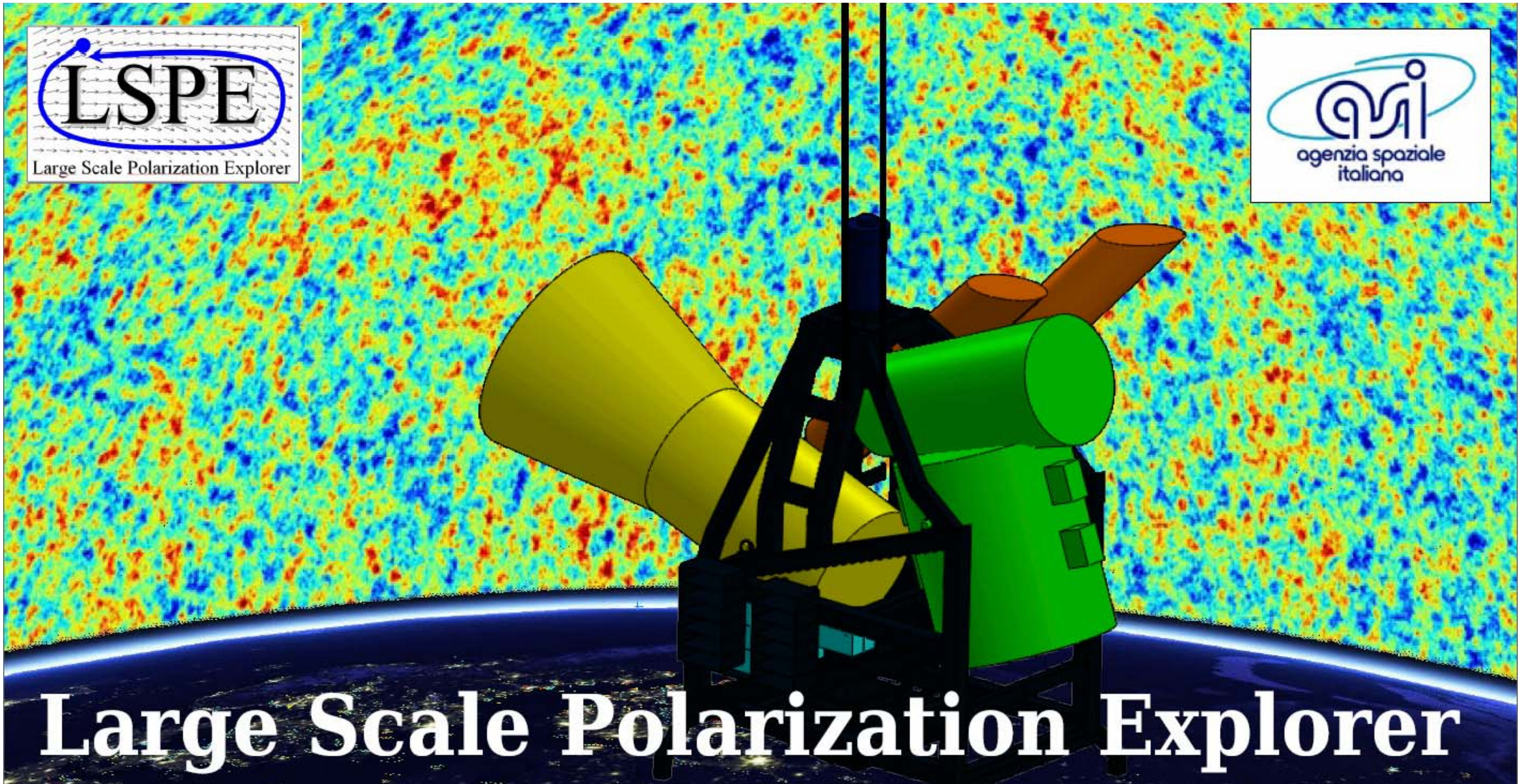
Superspec, astro-ph/1211.1652
Kovacs et al. SPIE 8452 (2012)



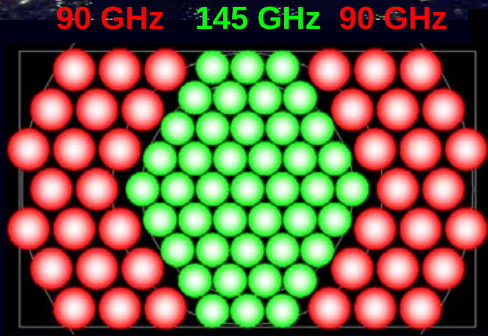
Deshima, Endo et a. APL 103 (2013)

LSPE
Large Scale Polarization Explorer

agenzia spaziale italiana



Large Scale Polarization Explorer



SAPIENZA UNIVERSITÀ DI ROMA
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
IASF bo
IEIIT
IFAC
UNIVERSITY OF CAMBRIDGE
MANCHESTER 1824

OLIMPO

(PI S. Masi, La Sapienza, Roma)

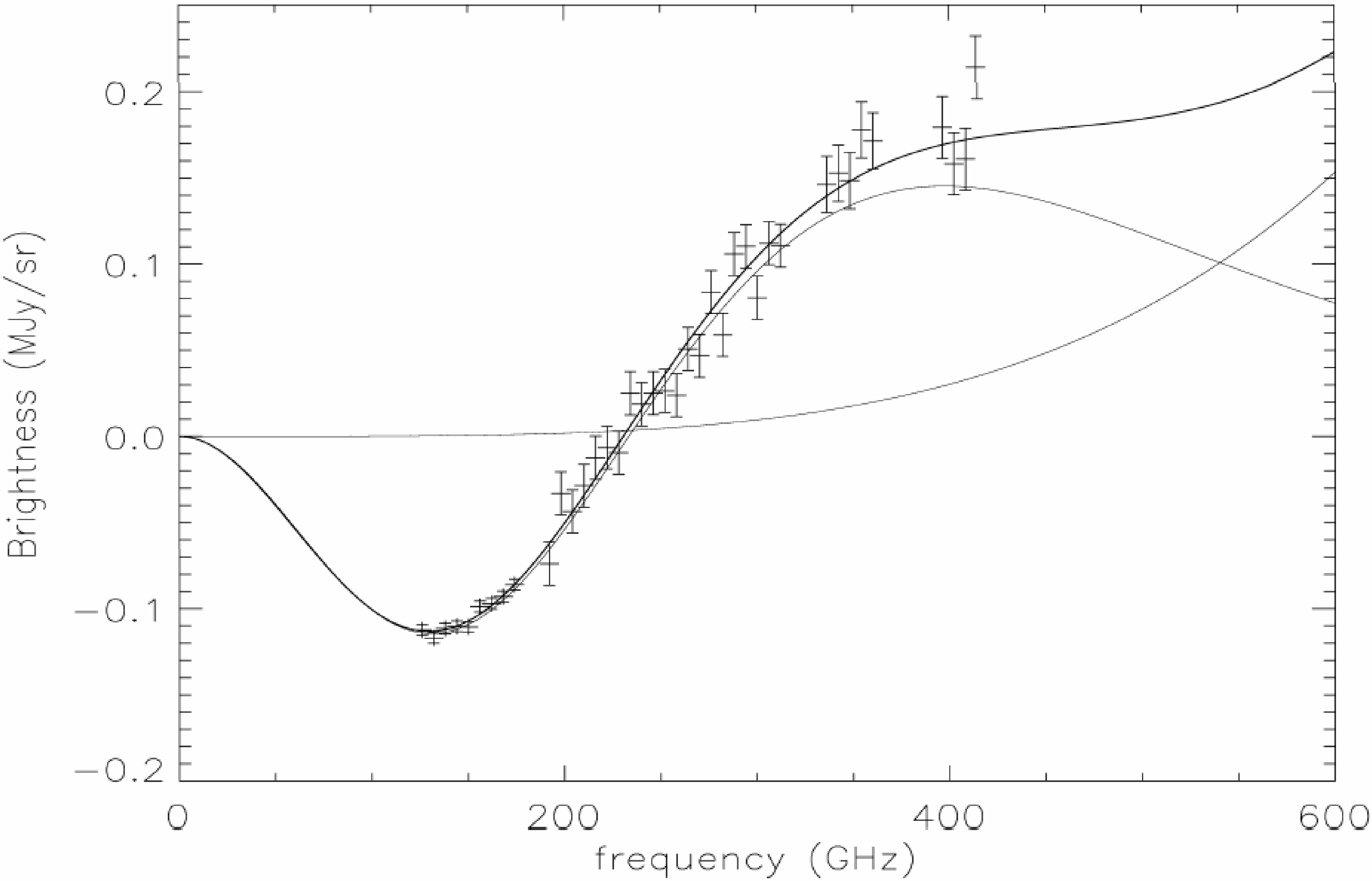
agenzia spaziale italiana

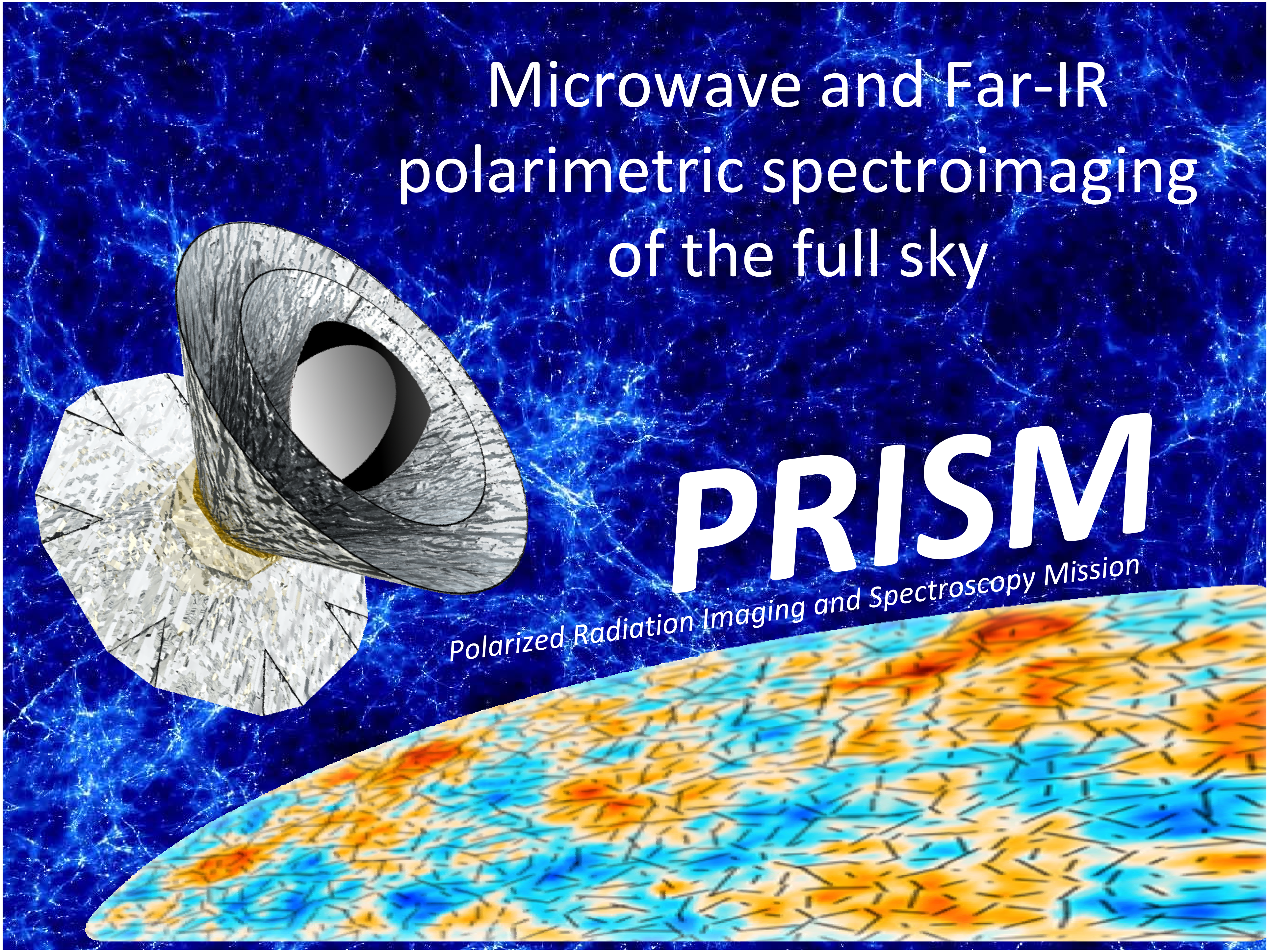
- Long Duration Balloon experiment for mm and sub-mm astronomy
- Operate from the stratosphere
- Launch from Svalbard
- Cassegrain, 2.6 m primary with scanning capability
- Multi-frequency array of bolometers

ch	ν_{eff} [GHz]	$\Delta\nu_{FWHM}$ [GHz]	Res. [‘]
I	148.4	21.5	4.2
II	215.4	20.6	2.9
III	347.7	33.1	1.8
IV	482.9	54.2	1.8

OLIMPO

(PI S. Masi, La Sapienza, Roma)





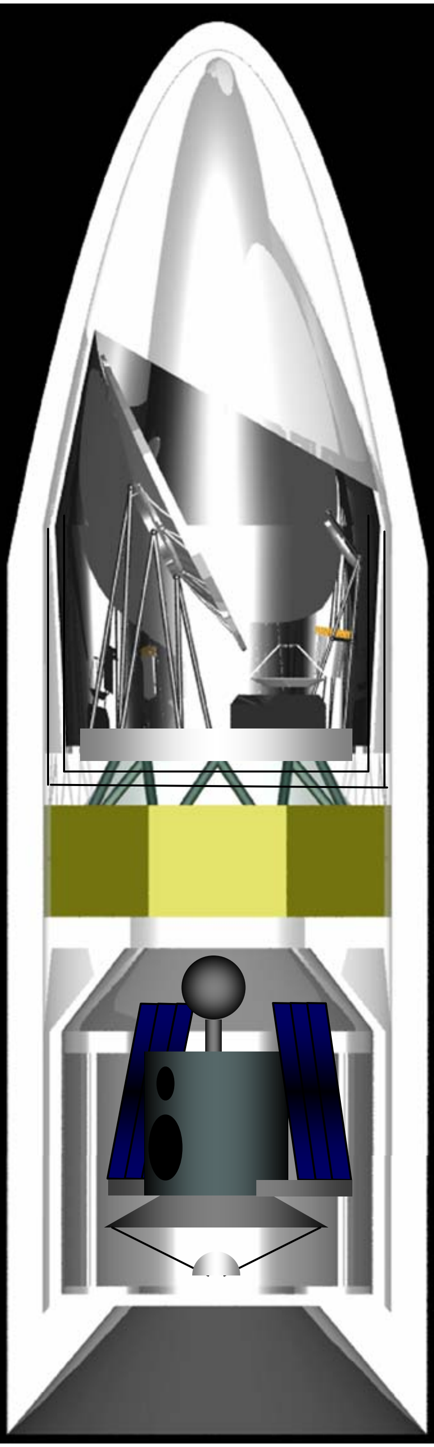
Microwave and Far-IR polarimetric spectroimaging of the full sky

PRISM

Polarized Radiation Imaging and Spectroscopy Mission

Strawman mission

- PRISM will cover the 30 GHz – 6 THz frequency range with two instruments:
  - A thousands-pixels **polarimetric imager** with 30 broad *diffraction limited* bands ($\Delta\nu/\nu\approx0.25$), plus Galactic lines monitors (either narrow bands or spectrometers on chip with $\delta\nu/\nu\approx0.025$). Its sensitivity will be limited by intrinsic photon noise, minimized by cooling the 3.5m telescope to <10K. Its optical axis is offset from the spin axis by 30°.
  - An **absolute spectrometer** cooled to 2.7K, with an angular resolution of 1.4°, and both a high and a low spectral resolution observing mode ($\Delta\nu\approx0.5$ GHz and 15 GHz respectively). Its optical axis is aligned to the spin axis.
- The platform will orbit around the **L2** Sun-Earth Lagrange point.
- A **companion satellite** will provide c**alibrators** for in-flight beam and polarization mapping, and a high-gain pointing antenna for high data-rate telemetry.



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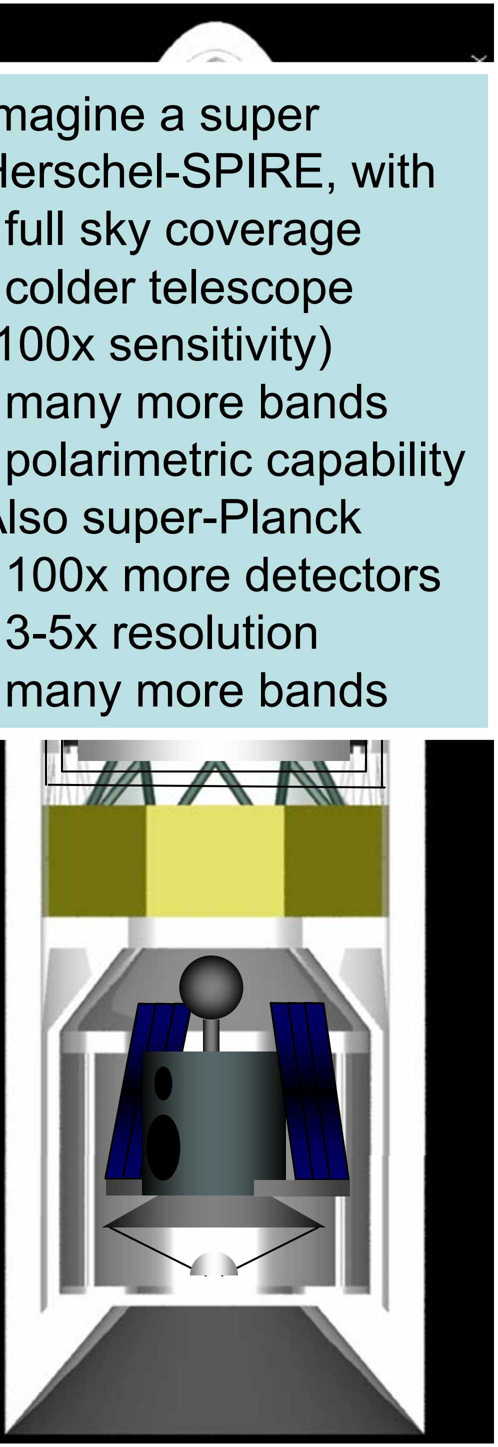
Imagine a super Herschel-SPIRE, with
- full sky coverage
- colder telescope (100x sensitivity)
- many more bands
- polarimetric capability

Also super-Planck
- 100x more detectors
- 3-5x resolution
- many more bands



Strawman mission

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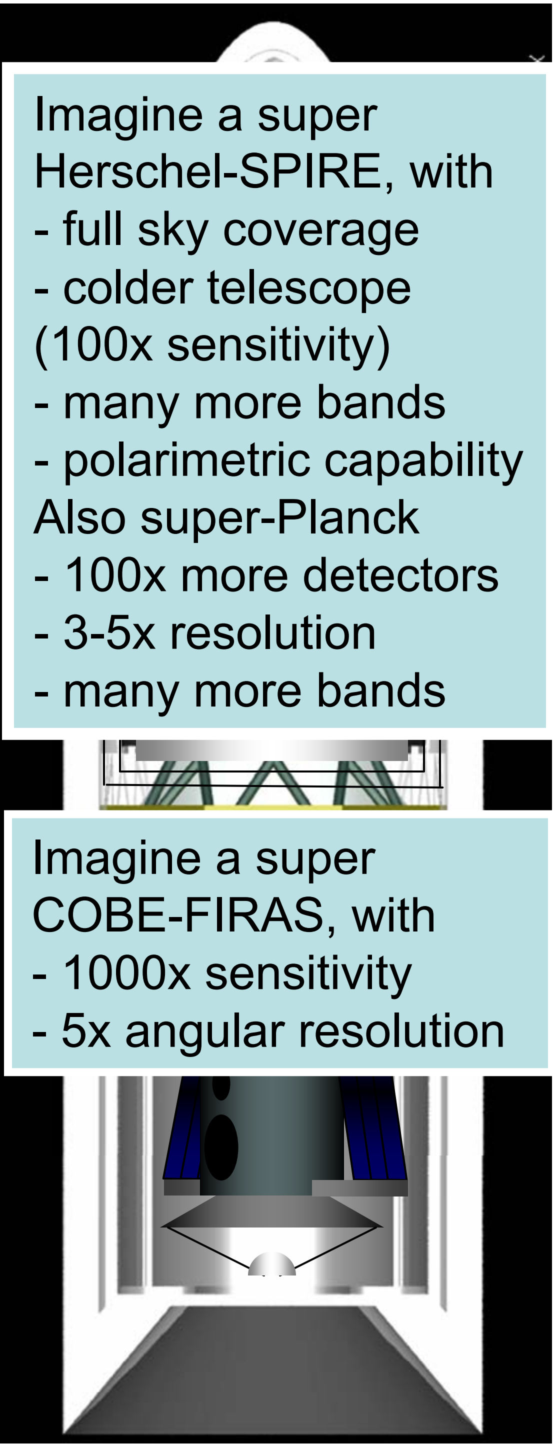
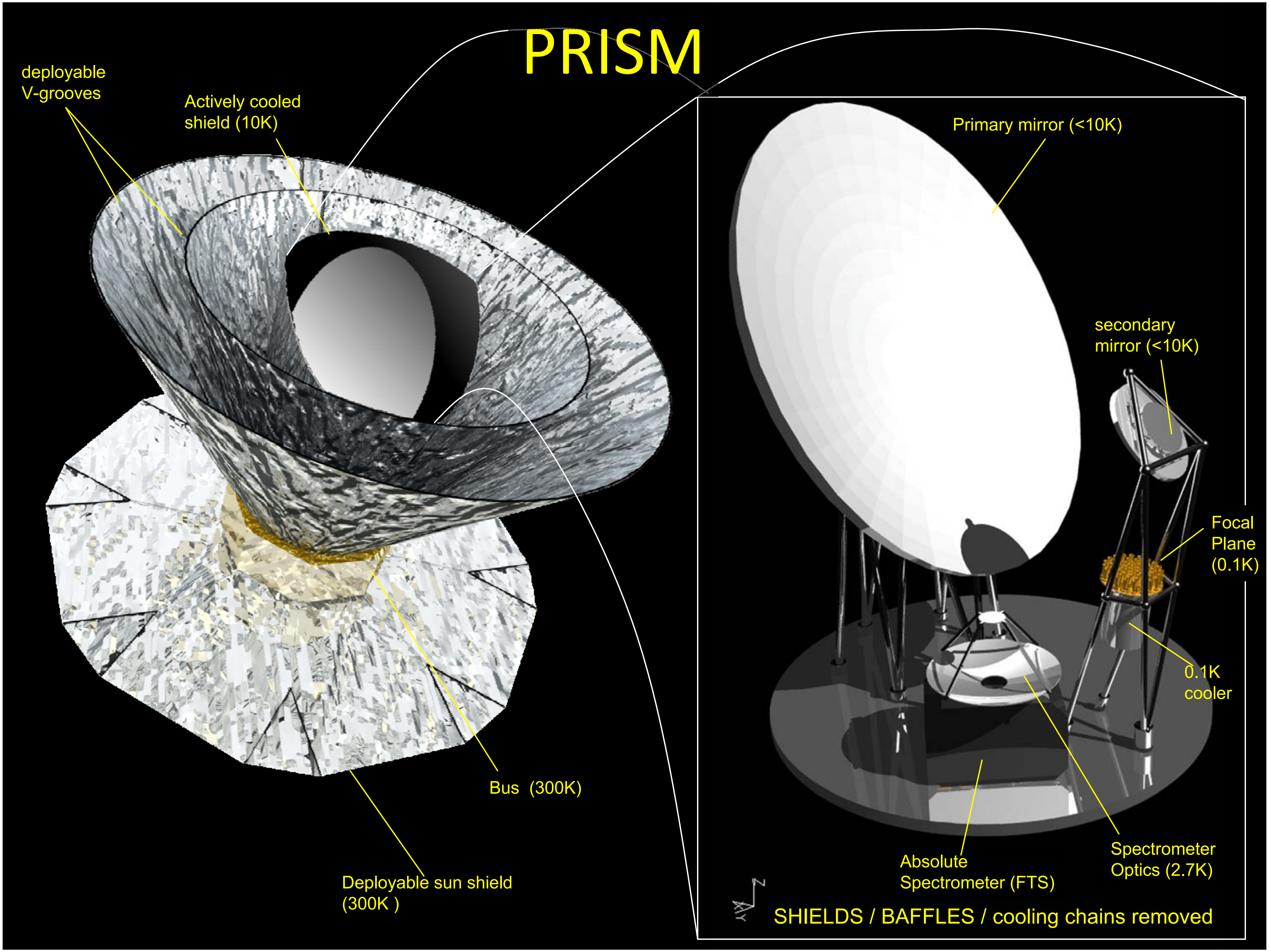


Imagine a super Herschel-SPIRE, with
- full sky coverage
- colder telescope (100x sensitivity)
- many more bands
- polarimetric capability

Also super-Planck
- 100x more detectors
- 3-5x resolution
- many more bands

Imagine a super COBE-FIRAS, with
- 1000x sensitivity
- 5x angular resolution

PRISM

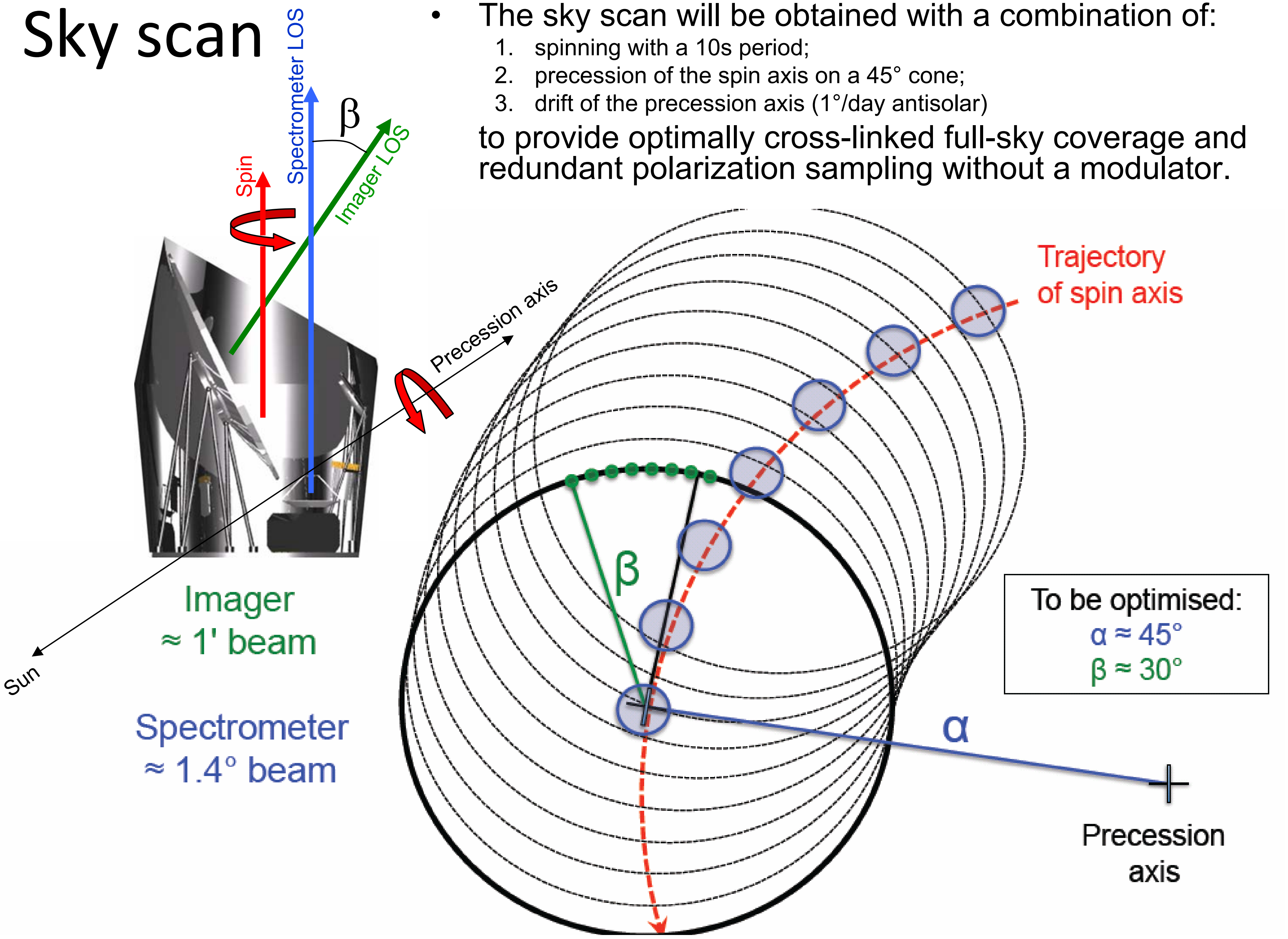


SHIELDS / BAFFLES / cooling chains removed

Sky scan

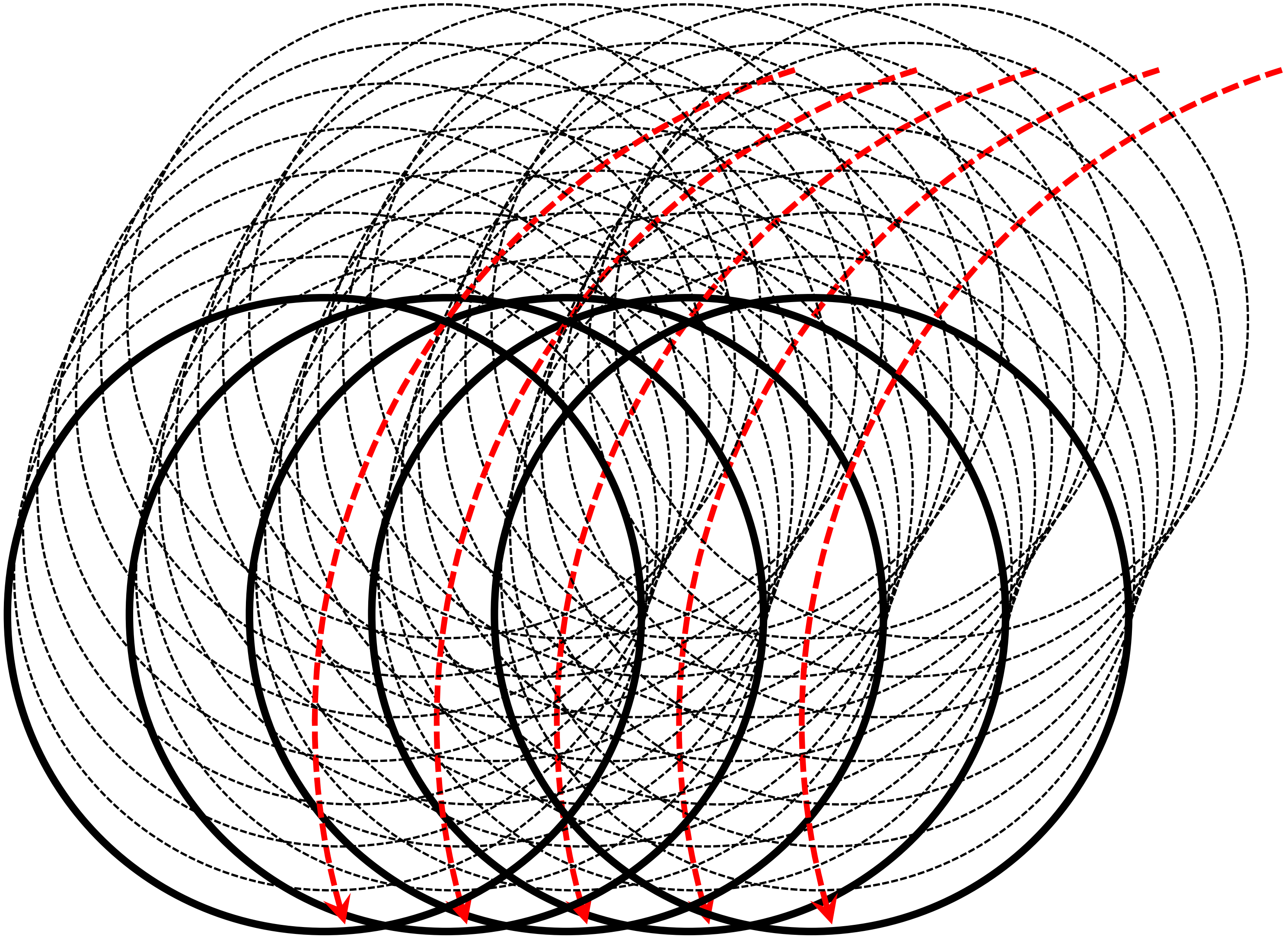
- The sky scan will be obtained with a combination of:
  1. spinning with a 10s period;
  2. precession of the spin axis on a 45° cone;
  3. drift of the precession axis (1°/day antisolar)

  to provide optimally cross-linked full-sky coverage and redundant polarization sampling without a modulator.



To be optimised:
α ≈ 45°
β ≈ 30°

- As the precession axis is being moved, each pixel is visited by each detector of the imager in every possible orientation.



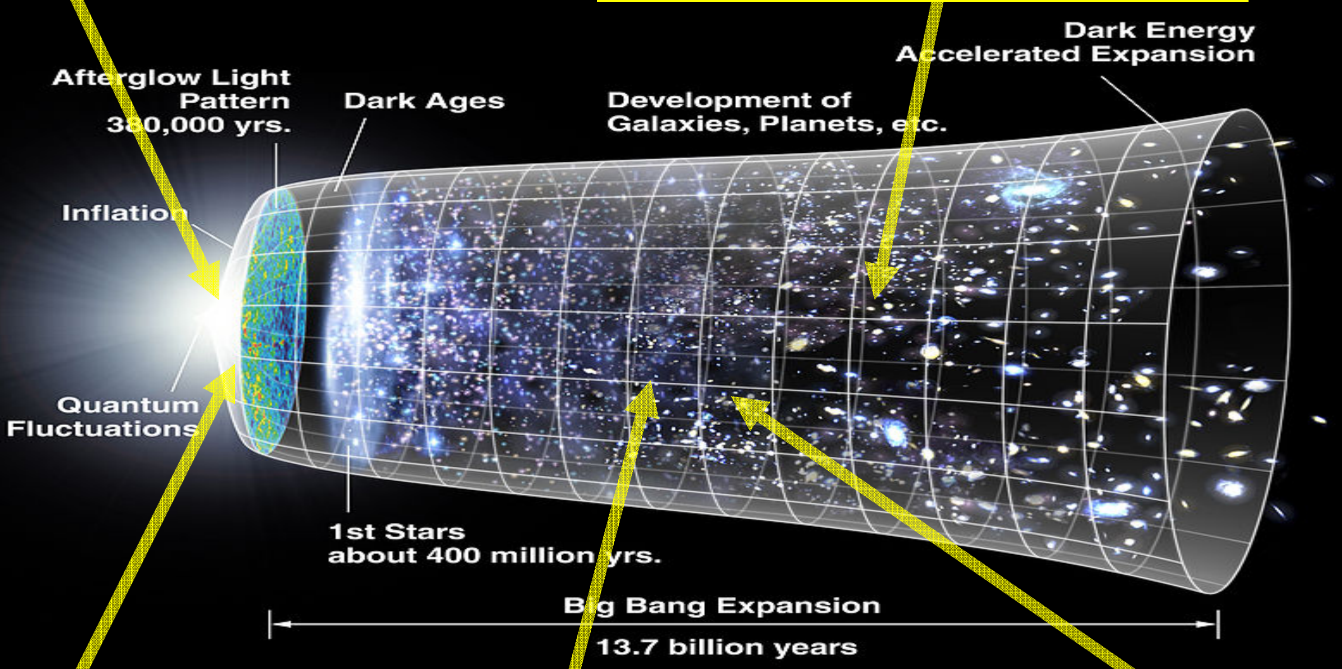
Synergy of the two instruments (1+1>2)

- Both instruments observe through the same zodiacal emission and detect variable sources **at the same time**.
- The absolute spectrometer measurements are contaminated by foreground sources in its wide beam. These are monitored and corrected for using narrow-beam imager data.
- Absolute spectrometer data are essential to set the zero-level of the imager maps
- Absolute spectrometer data are essential to get an accurate relative calibration of the imager channels, especially the high frequency ones (0.05% !).
- In this way the absolute calibration is transferred to the spectropolarimeter, so that **high-resolution absolute maps are produced enabling high-accuracy components separation**.

In a nutshell: New science with a polarimetric and spectral survey of the **Hubble volume** from the μ–wave to the far-IR

Ultimate measurement of CMB polarization, Gaussianity, and absolute spectrum.
Search for the gravitational waves produced during inflation.

Ultimate galaxy cluster survey via Sunyaev-Zeldovich effect (SZ): ($>10^6$: all clusters with $M>10^{14}M_\odot$ within our horizon)



Probe epochs before recombination and new physics using CMB spectral distortion measurements

Map the gravitational potential all the way to z=1100 through CMB lensing

Probe early star formation and its evolution through precision characterization of the Cosmic Infrared Background (CIB)

In a nutshell: New science with a polarimetric and spectral survey of the **Hubble volume** from the μ–wave to the far-IR

5

Ultimate measurement of CMB polarization, Gaussianity, and absolute spectrum.
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1

Ultimate galaxy cluster survey
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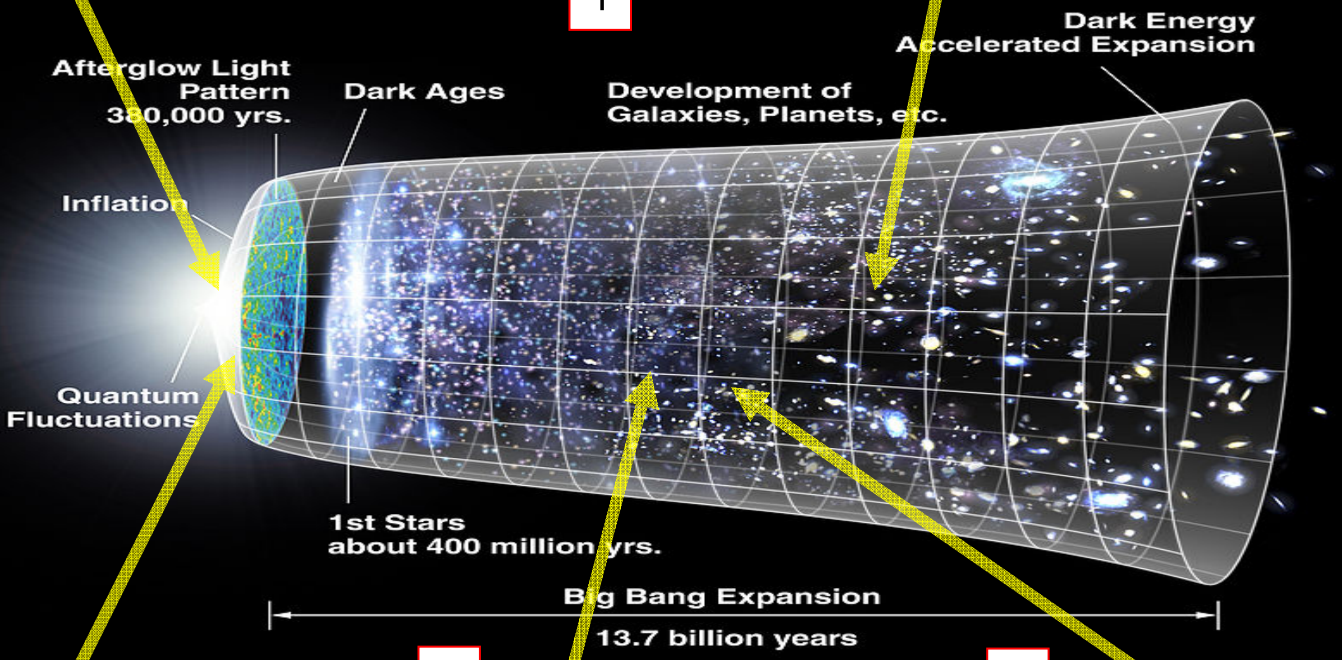

4

Probe epochs before recombination and new physics using CMB spectral distortion measurements

3

Map the gravitational potential all the way to z=1100 through CMB lensing

2

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In a nutshell: New science with a polarimetric and spectral survey of the **Hubble volume** from the μ–wave to the far-IR

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Ultimate measurement of CMB polarization, Gaussianity, and absolute spectrum.
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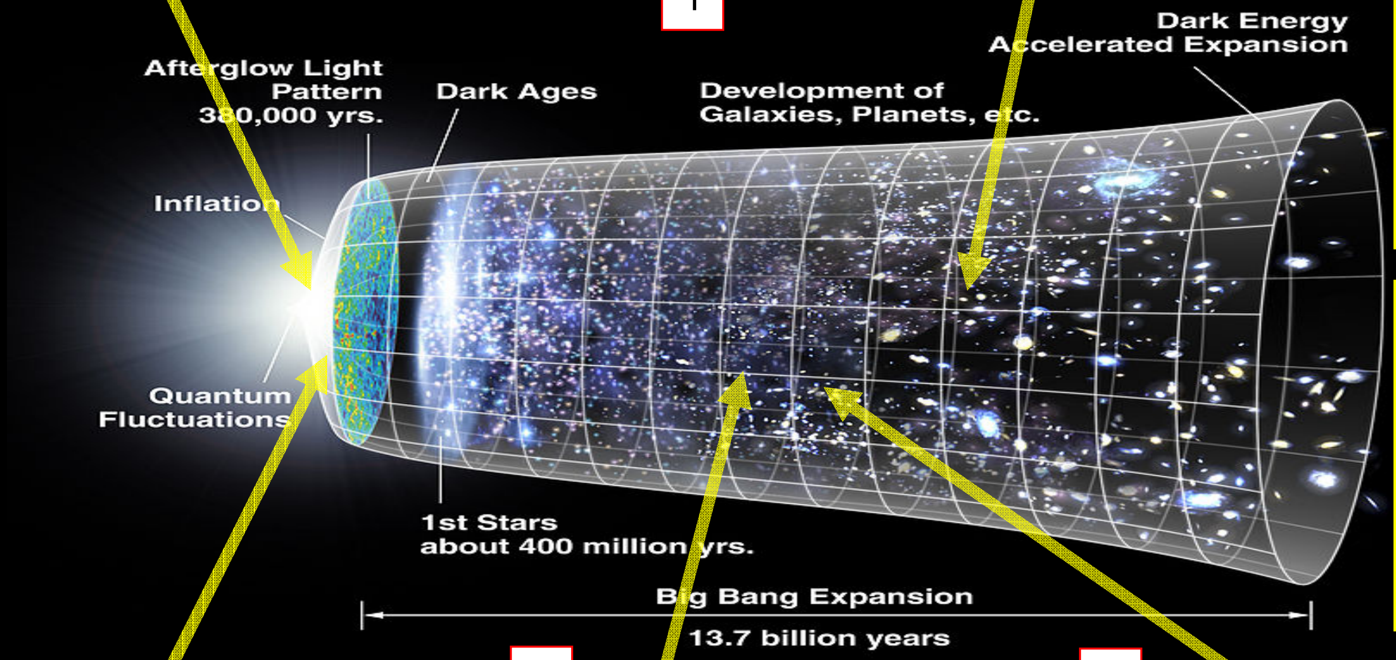
1

Ultimate galaxy cluster survey
via Sunyaev-Zeldovich effect (SZ):
($>10^6$: all clusters with $M>10^{14}M_\odot$ within our horizon)

Legacy archive of hundreds of full-sky intensity and polarization maps from tens of GHz to few THz with extreme precision and resolution :
$1\mu K_{CMB}$arcmin
1'FWHM@λ1mm

6



A complete survey of the interstellar medium in the Milky way : dust, molecular lines, magnetic field, …

4

Probe epochs before recombination and new physics using CMB spectral distortion measurements

3

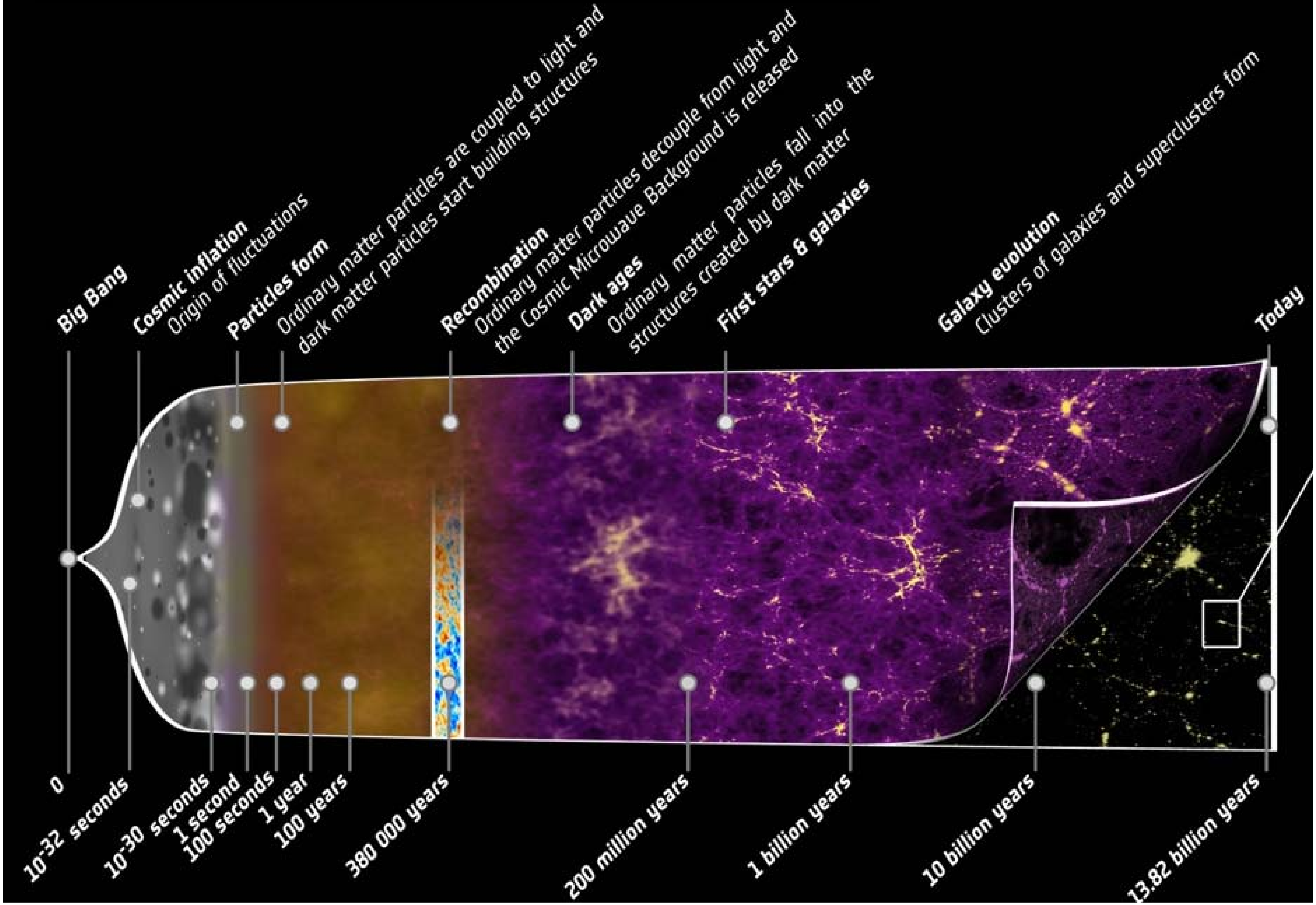
Map the gravitational potential all the way to z=1100 through CMB lensing

2

Probe early star formation and its evolution through precision characterization of the Cosmic Infrared Background (CIB)

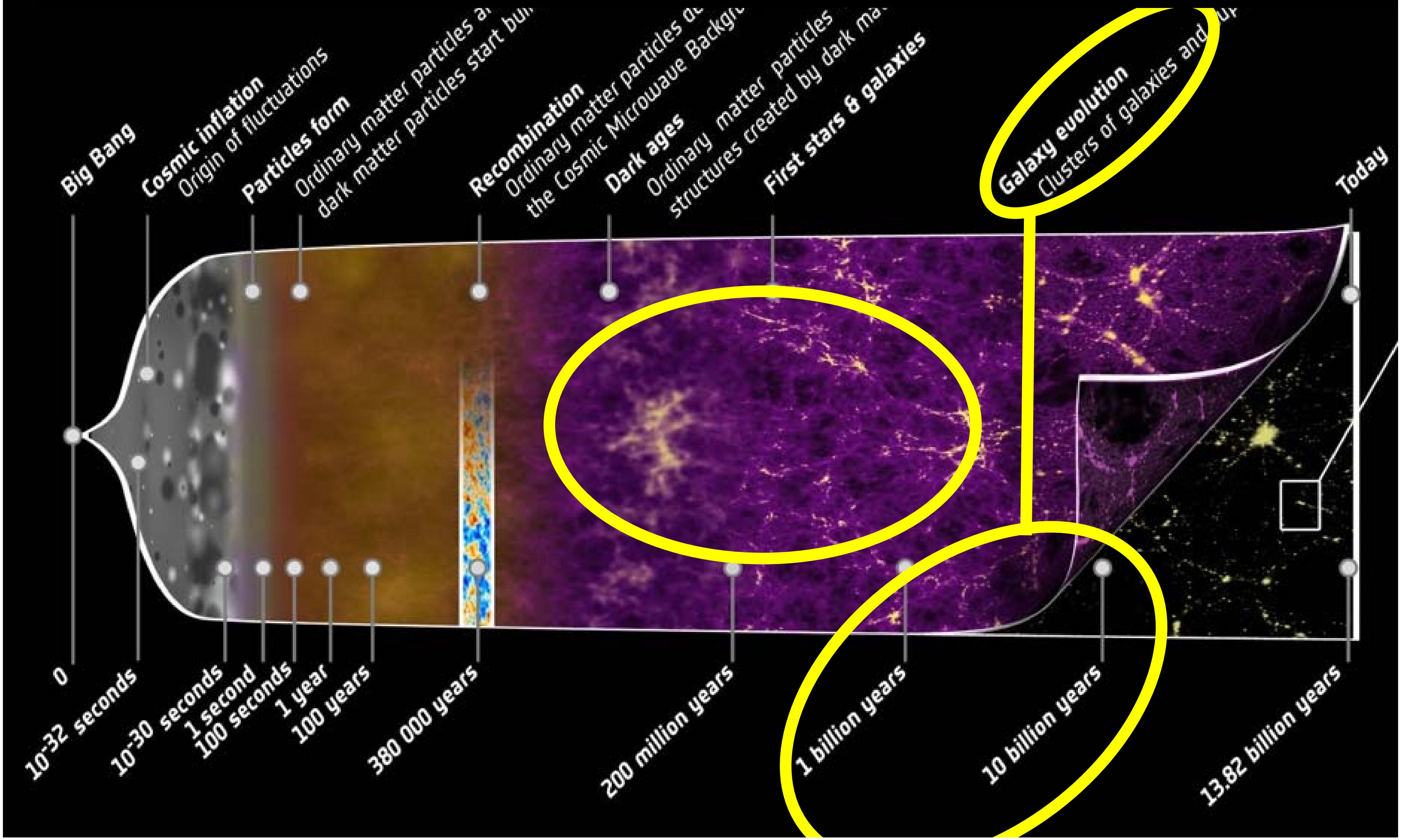
Main science goals (cosmology)

1 2 3 4 5



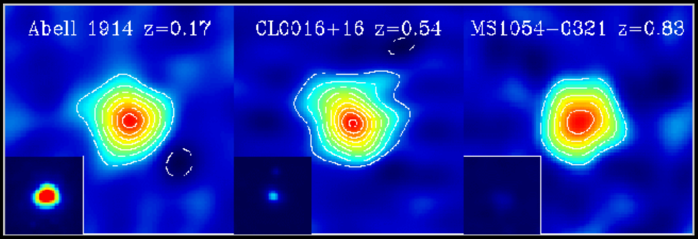
PRISM probes cosmic structures in the mm/FIR, using :

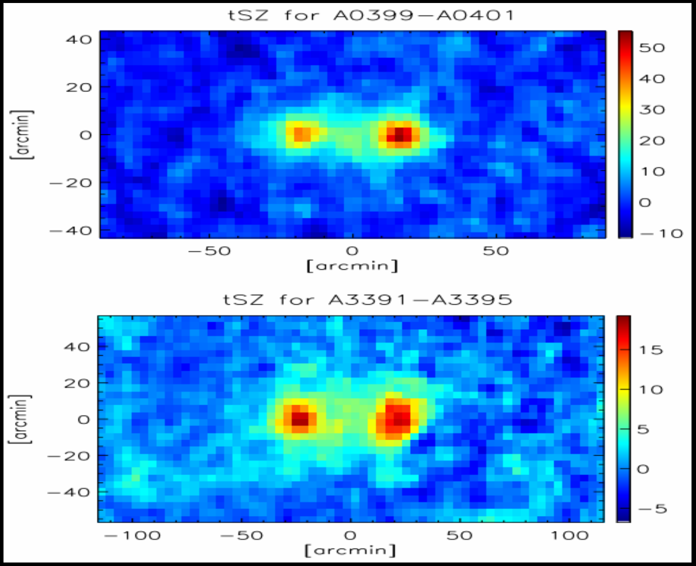
- Sunyaev-Zeldovich effect in galaxy clusters (mapping hot baryonic gas)
- Lensing of CMB fluctuations (mapping dark matter and probing dark energy)
- Early dusty galaxies (characterizing early star formation)

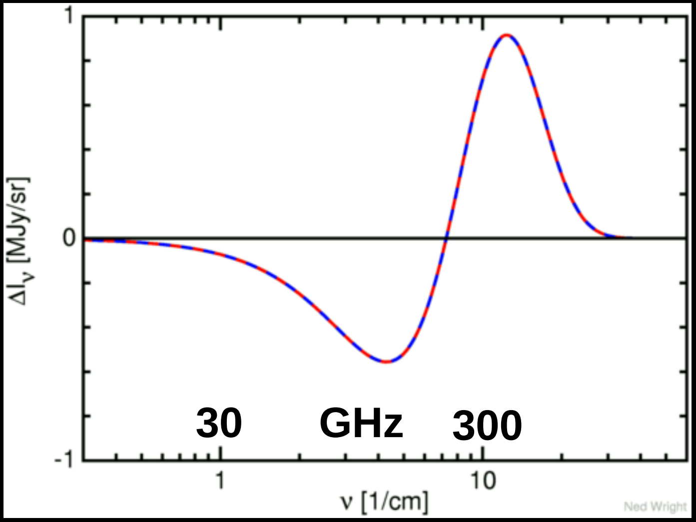


Probing the Universe with galaxy clusters

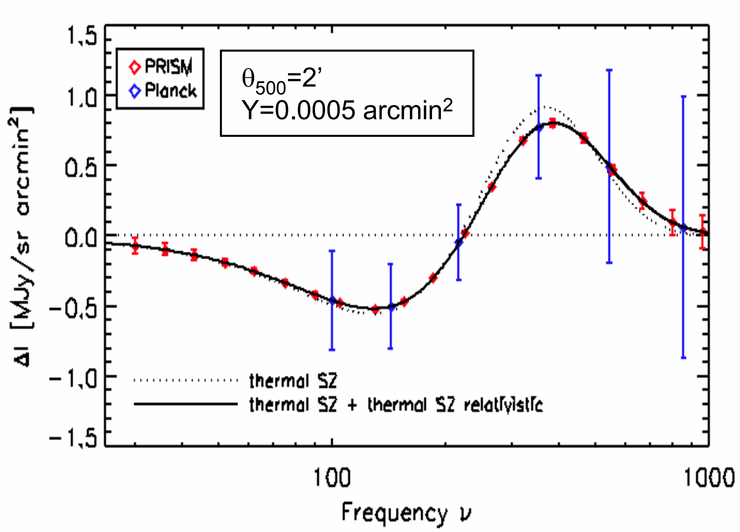
- CMB photons undergo inverse Compton scattering against electrons in the intracluster plasma (**Sunyaev-Zeldovich effect, SZ**).
- Amplitude **does not depend on redshift**, allowing clusters and their peculiar velocities to be mapped everywhere in Hubble volume
- At variance with X-ray emission from the same gas, the **SZ signal depends linearly on the density** of the gas, detecting it even in the periphery of the clusters and in low density filaments
- The **unique spectral shape** distinguishes the SZ from other galactic and extragalactic contaminants





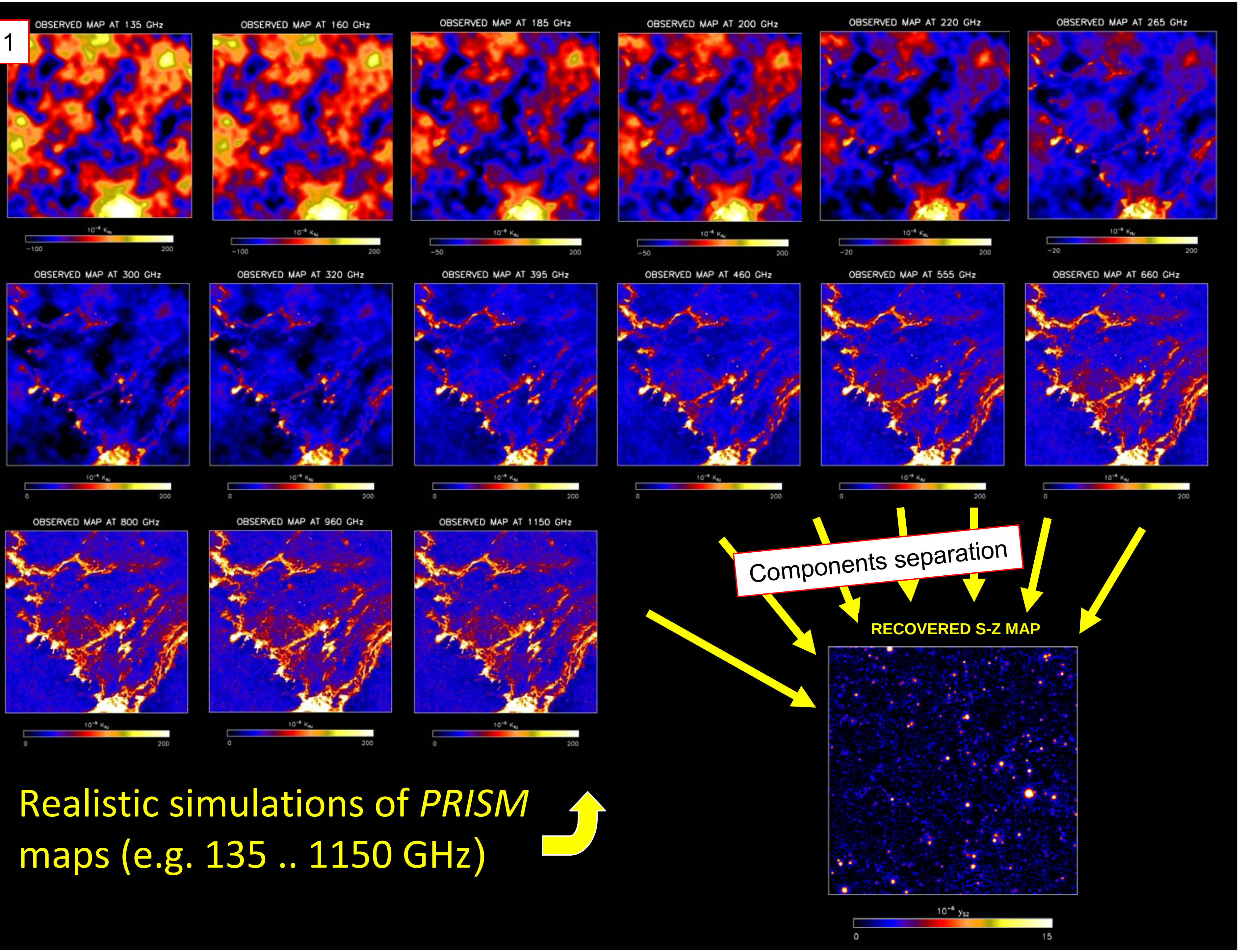


Probing the Universe with galaxy clusters



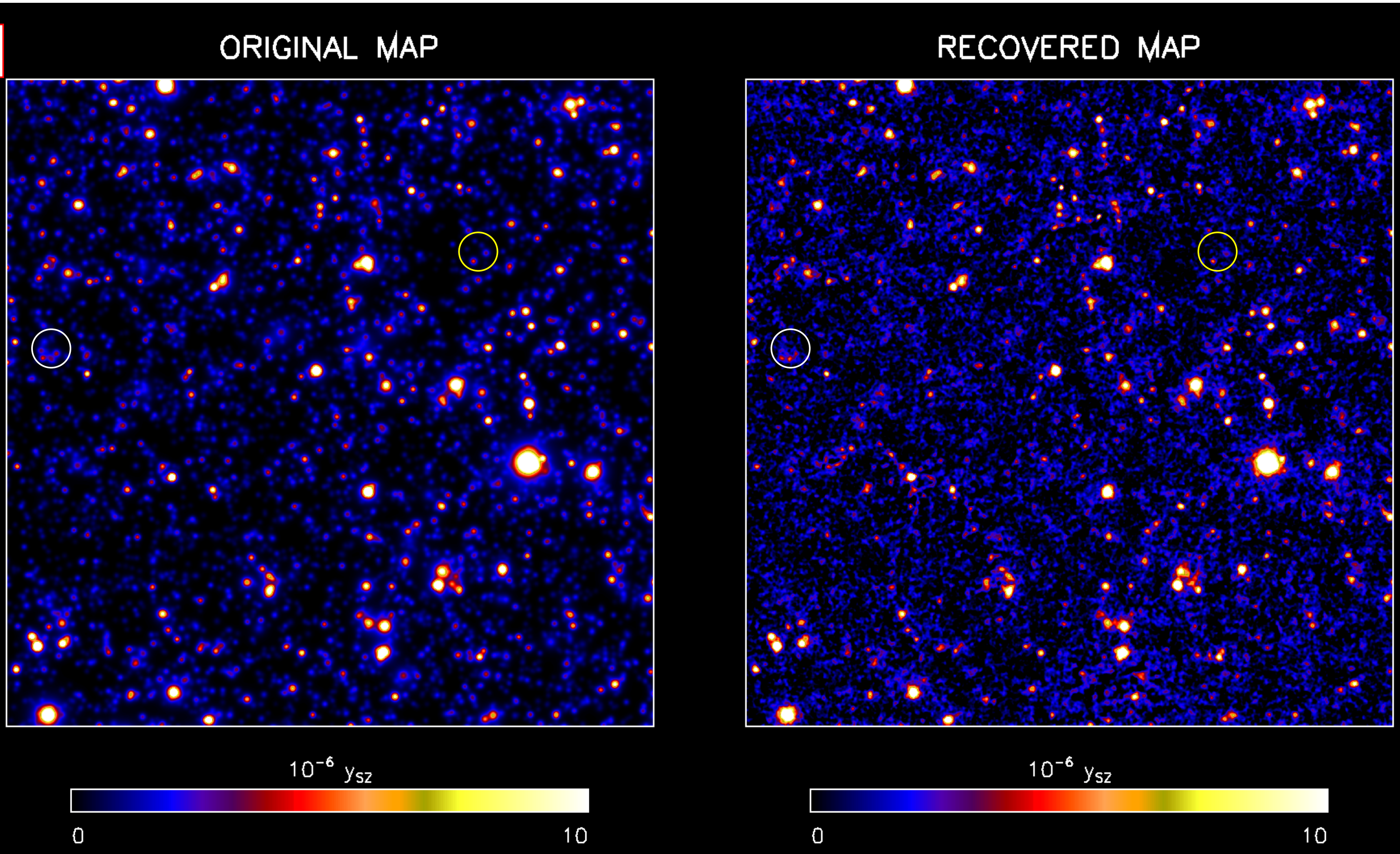
- The combination of extreme sensitivity, broad spectral coverage, and angular resolution of ***PRISM*** are used to separate the SZ component cleanly from other foregrounds, allowing the following new science:
  - detect cluster and groups systems **throughout the Hubble volume** from the moment just after their formation.
  - Measure cluster mass to high redshift (z>4) through gravitational lensing of the CMB (temperature & polarization). **Detection limit below $10^{14}M_{\odot}$ at all redshifts.**
  - Measure the kinetic SZ effect, with typical errors of 50 km/s for individual clusters. **This (and only this) will allow mapping the *cosmic velocity field*. A new probe of dark energy and large scale structure.**

1



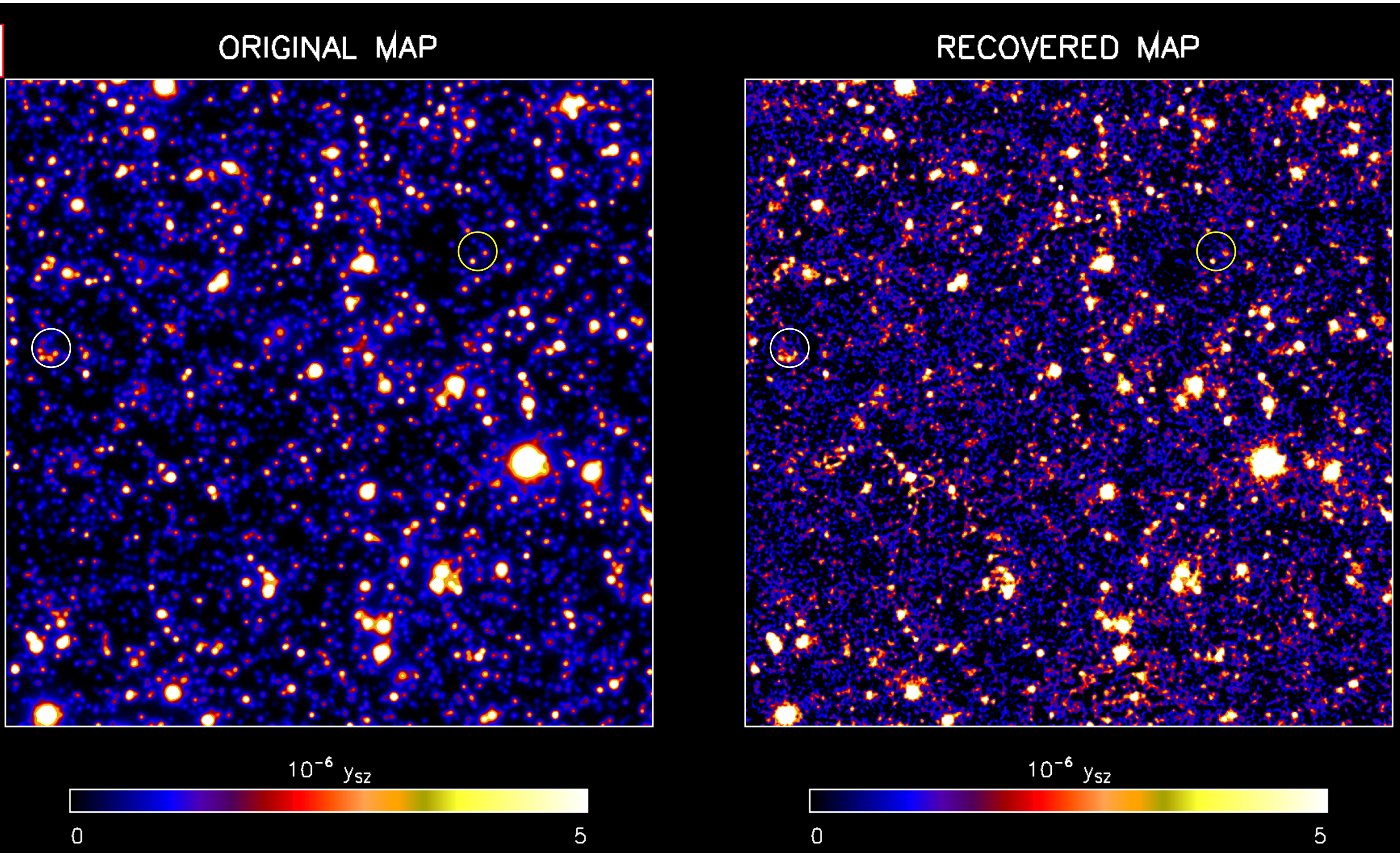
Components separation

Realistic simulations of *PRISM* maps (e.g. 135 .. 1150 GHz)



- reconstruction of the SZ effect at about 1.3’ resolution on a 3.4°x3.4° patch on the sky (only 0.025% of the actual sky coverage of PRISM).
- The simulation includes SZ matching from a population of clusters matching Planck number counts, CIB, CMB, infrared sources and dust as observed with Herschel and scaled using the Planck dust model, noise. The reconstruction is made with an harmonic ILC (not optimal) using 15 PRISM channels from 135 to 1150 GHz.

1


ORIGINAL MAP

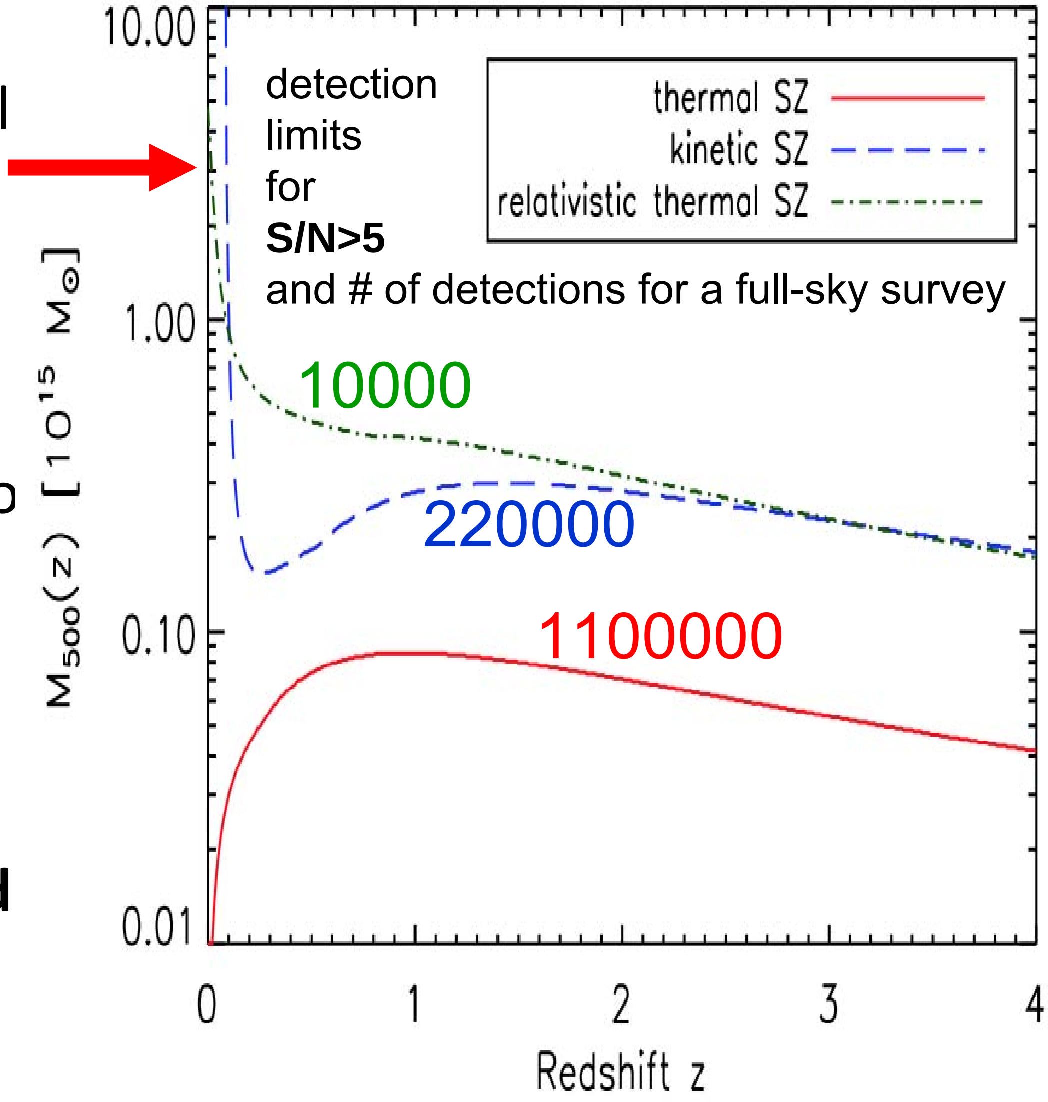
RECOVERED MAP

- reconstruction of the SZ effect at about 1.3’ resolution on a 3.4^{o}x3.4^{o} patch on the sky (only 0.025% of the actual sky coverage of PRISM).
- The simulation includes SZ matching from a population of clusters matching Planck number counts, CIB, CMB, infrared sources and dust as observed with Herschel and scaled using the Planck dust model, noise. The reconstruction is made with an harmonic ILC (not optimal) using 15 PRISM channels from 135 to 1150 GHz.

1

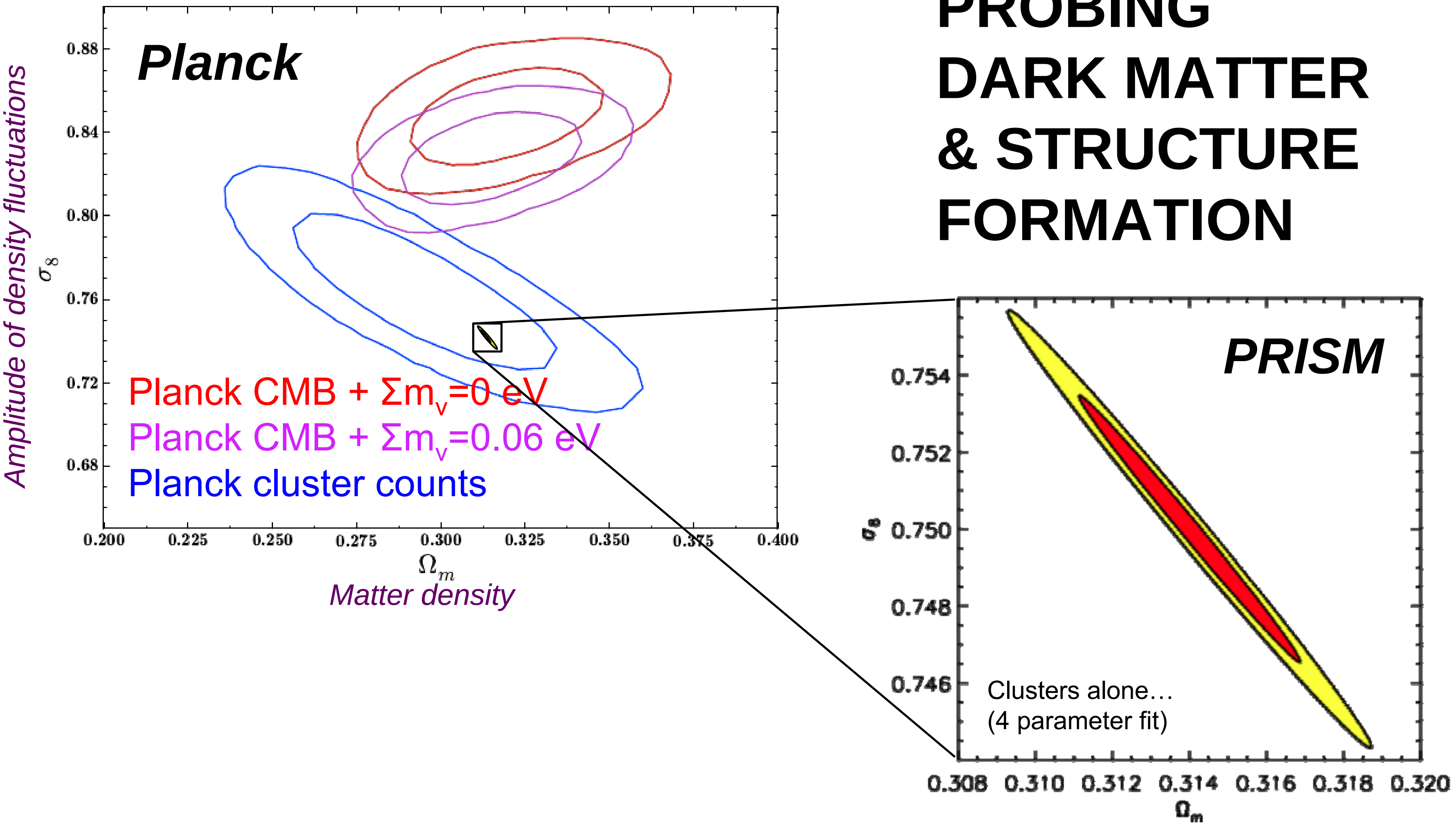
Probing the Universe with galaxy clusters

- **Cluster catalog:** realistic simulations show that the PRISM cluster catalogue wil include >10^6 clusters, with mass limit <$10^{14} M_\odot$ at all z.
- **Cosmology probe:** This will allow to constrain cosmological parameters (mainly σ_8 and Ω_m , but also w_a and w_o).
- **Cosmic velocity field**: The peculiar velocity of a few ~10^5 galaxy clusters will be measured
- **Relativistic corrections and non-thermal effects**: the temperature of the hot gas will be measured for ~10^4 galaxy clusters


detection limits for **S/N>5** and # of detections for a full-sky survey

Probing the Universe with galaxy clusters

PROBING DARK MATTER & STRUCTURE FORMATION



Probing the Universe with galaxy clusters

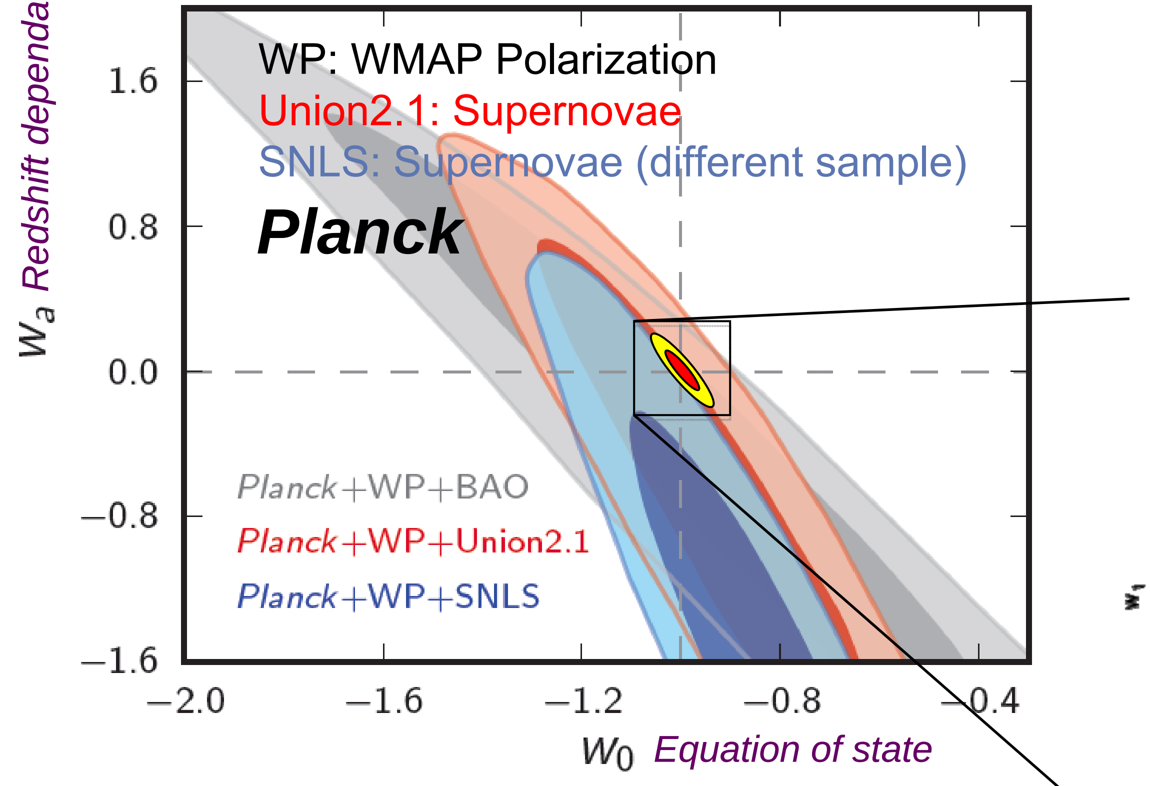
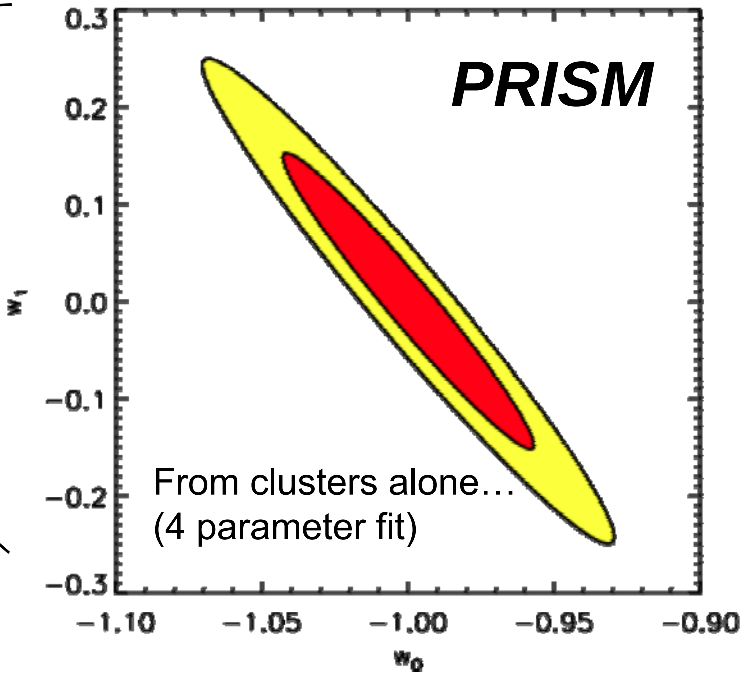


Fig. 36. 2D marginalized posterior distributions for w_0 and w_a, for the data combinations *Planck*+WP+BAO (grey), *Planck*+WP+Union2.1 (red) and *Planck*+WP+SNLS (blue). The contours are 68% and 95%, and dashed grey lines show the co

PROBING DARK ENERGY

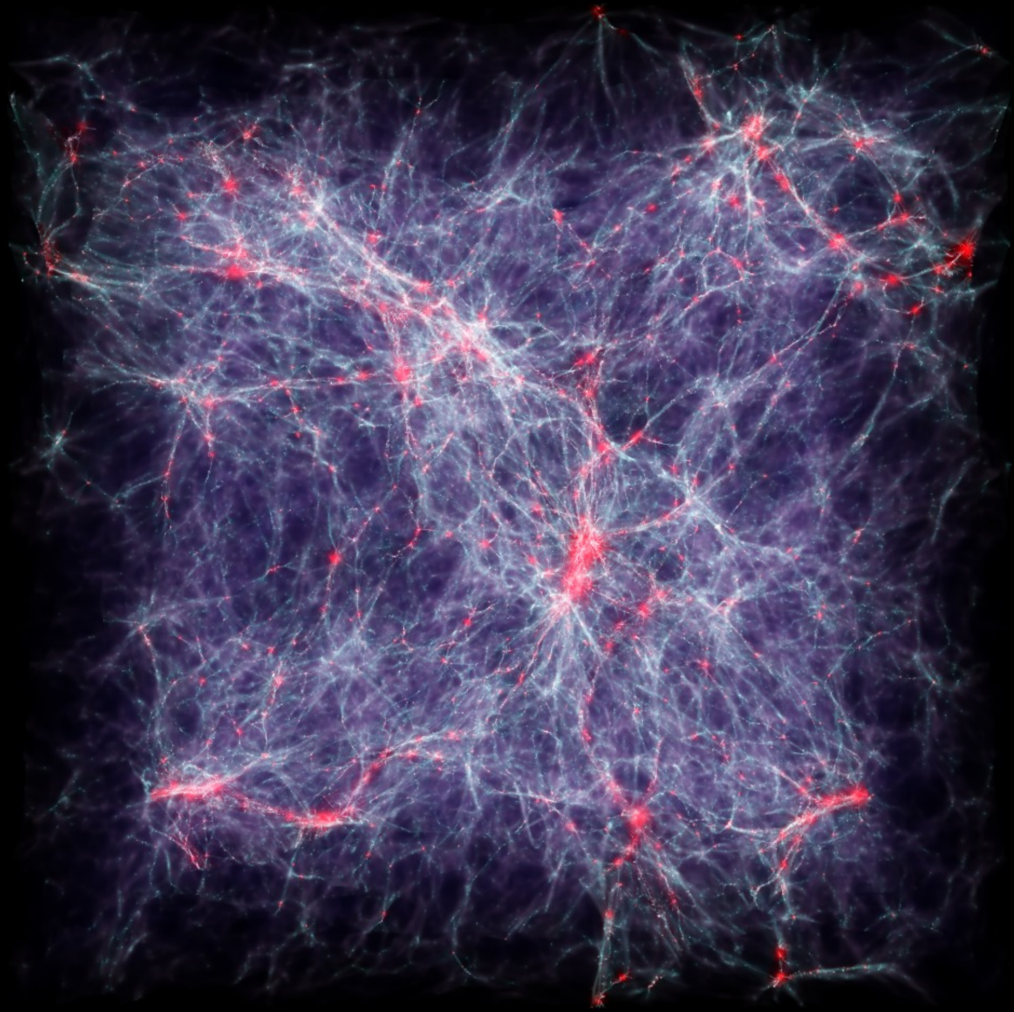


From clusters alone…
(4 parameter fit)

These constraints complement and improve those from other observations (like Euclid) since they are based on a deeper (higher redshift) survey and have a FoM~1000 (cfr. FoM=430 for Euclid Primary)

Detection of the cosmic web

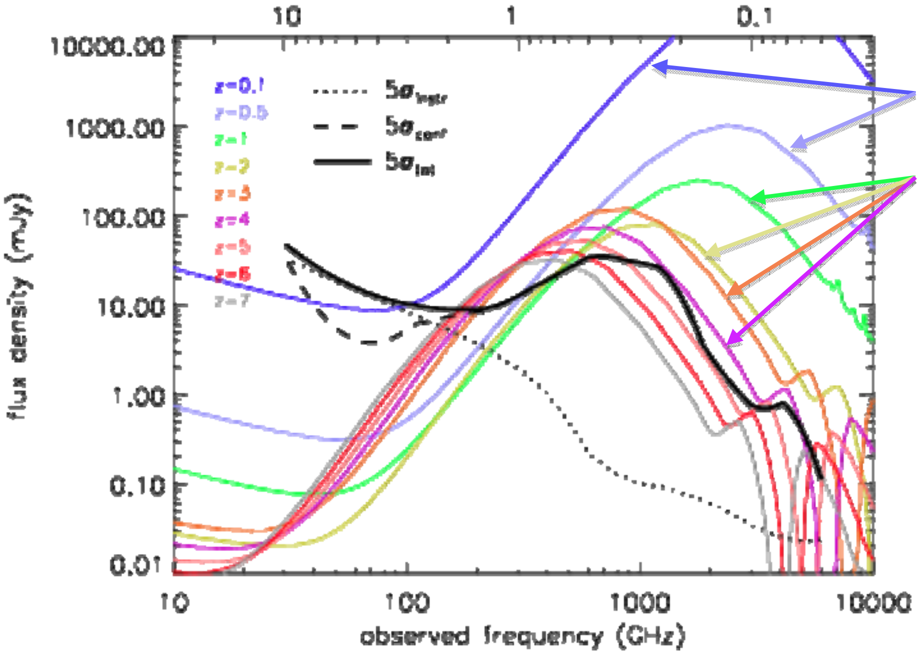
25 h^{-1} Mpc
Planck ΛCDM



In filaments:
$T \approx 10^5$-10^7 K
$\rho_{gas} \approx 5$-$200 \times \rho_{gas}$

➔PRISM will map the pressure (nT) distribution of the whole hot observable Universe

Dusty galaxies at z = 0.1–7 :

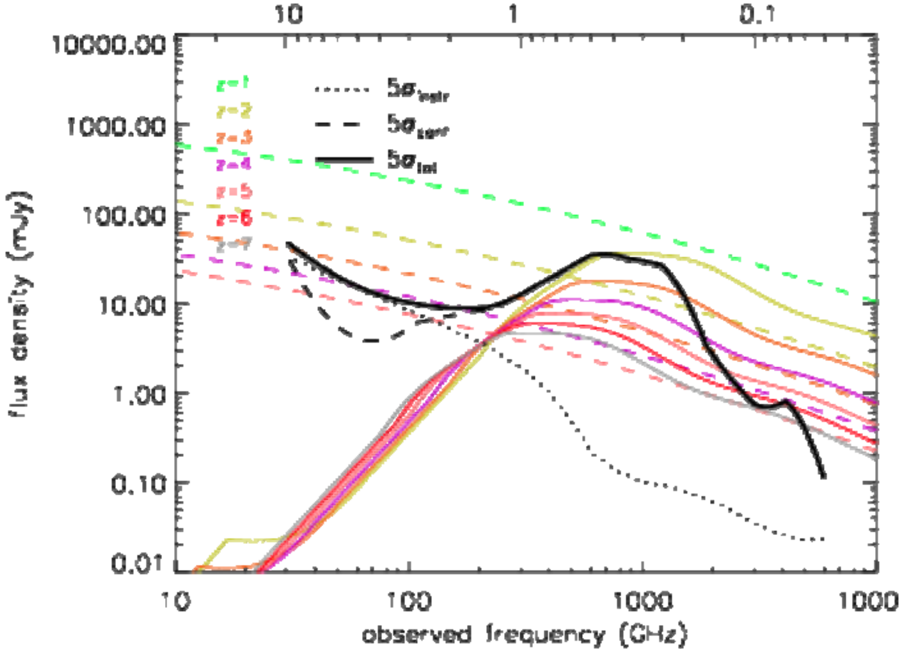


ARP 220 scaled to $L_{IR} = 10^{12}L_{\odot}$

SMM J2135-0102 ($z \approx 2.3$)

scaled to L_{IR} = 1-3 × $10^{13}L_{\odot}$

- Typical $L_{IR} = 10^{13}L_{\odot}$ type 2 QSO ———
- 3C 273 blazar - - - - -

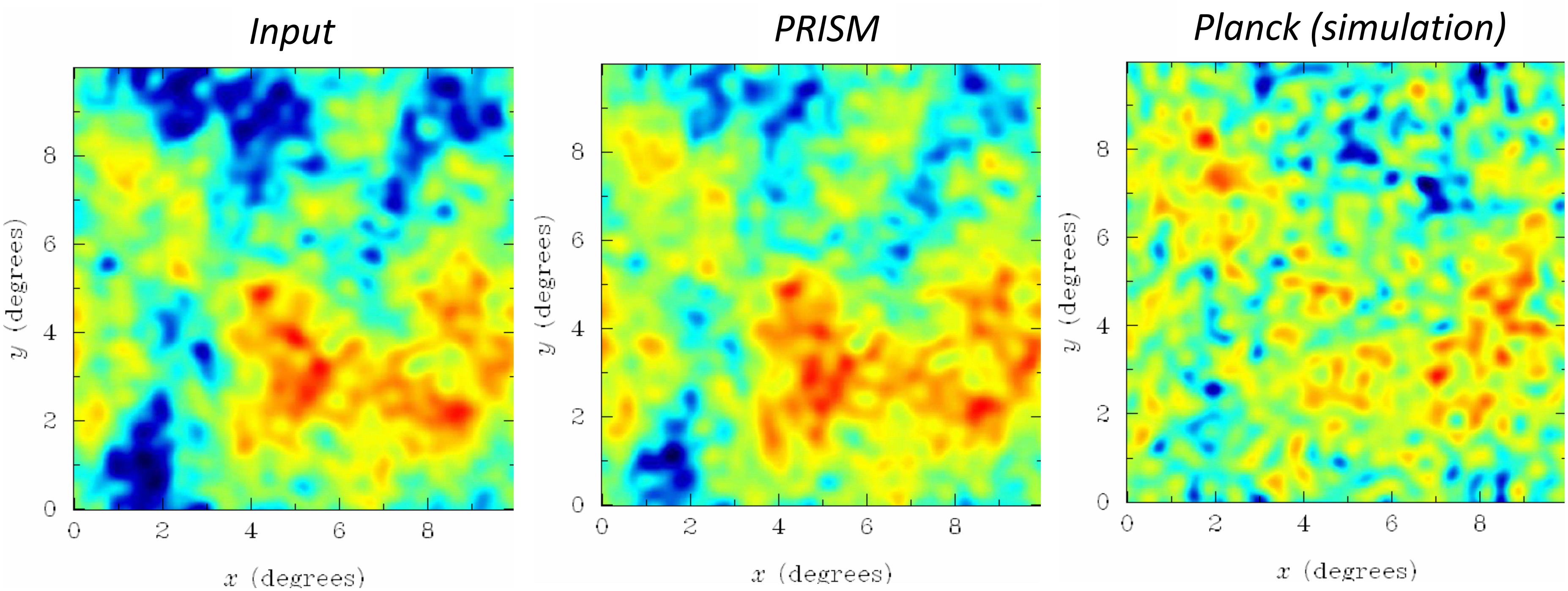


Detect thousands of strongly lensed galaxies (full sky)

Use the many frequency bands
- to separate dust from CIB (cover all peaks)
- to identify the nature of the sources
- to measure the total bolometric luminosities
- to measure photometric redshifts
- to bin the CIB emission in redshift shells

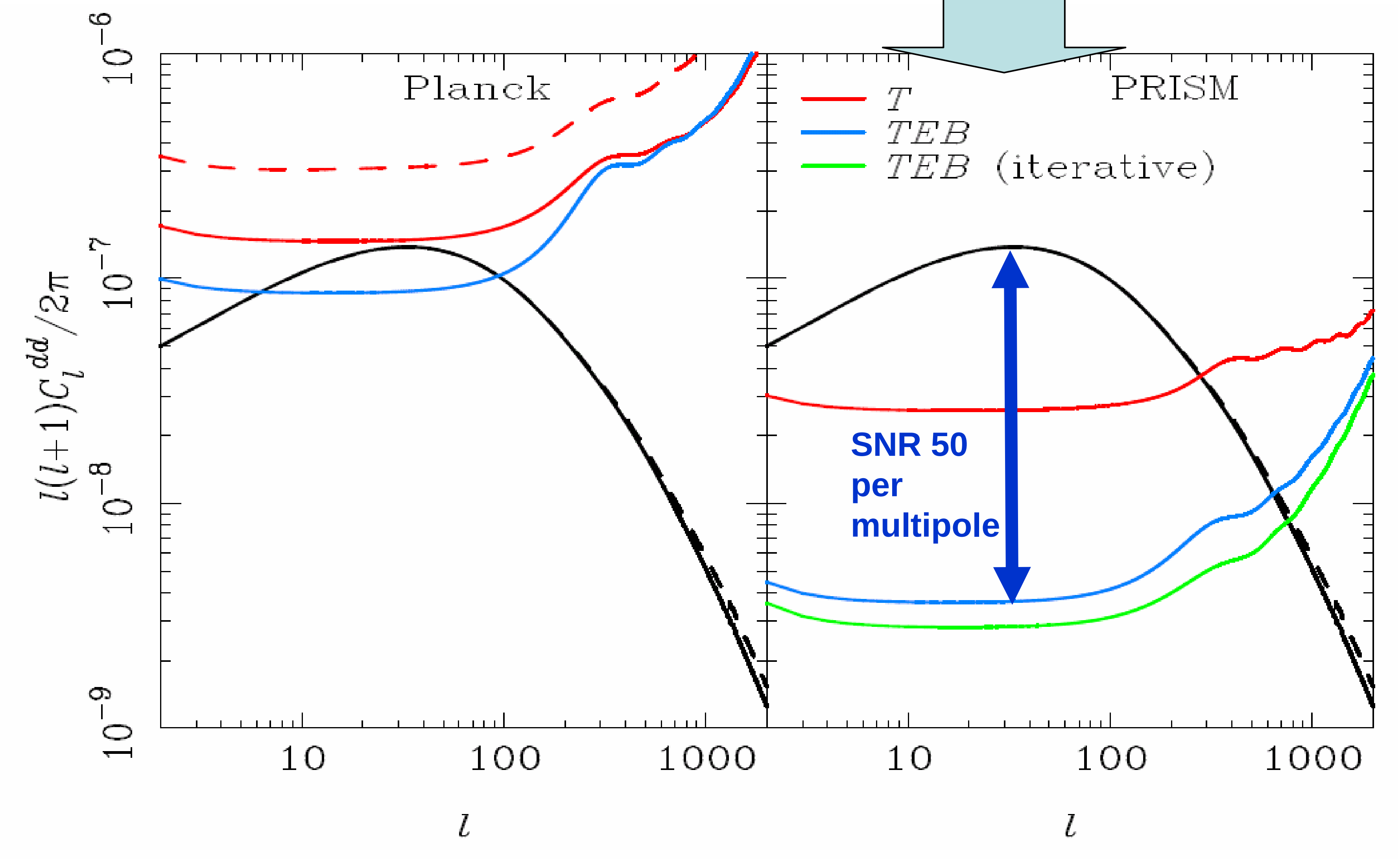
➔ A unique view of the highest z Universe

Reconstruction of the gravitational potential



- PRISM accurate measurements of CMB anisotropy and polarization produce high-fidelity reconstruction of the **LOS integral of the gravitational potential all the way to recombination.**
- These measurements nicely **complement and extend** what will be measured by Euclid, which is limited to redshifts < 1.5. The systematics are very different and cross-correlating both is a good way to control multiplicative biases in the galaxy lensing measurement.
- And you get CMB lensing for free!

PRISM lensing measurement



SNR 50 per multipole

3

Lensing potential correlation with tracers of LSS

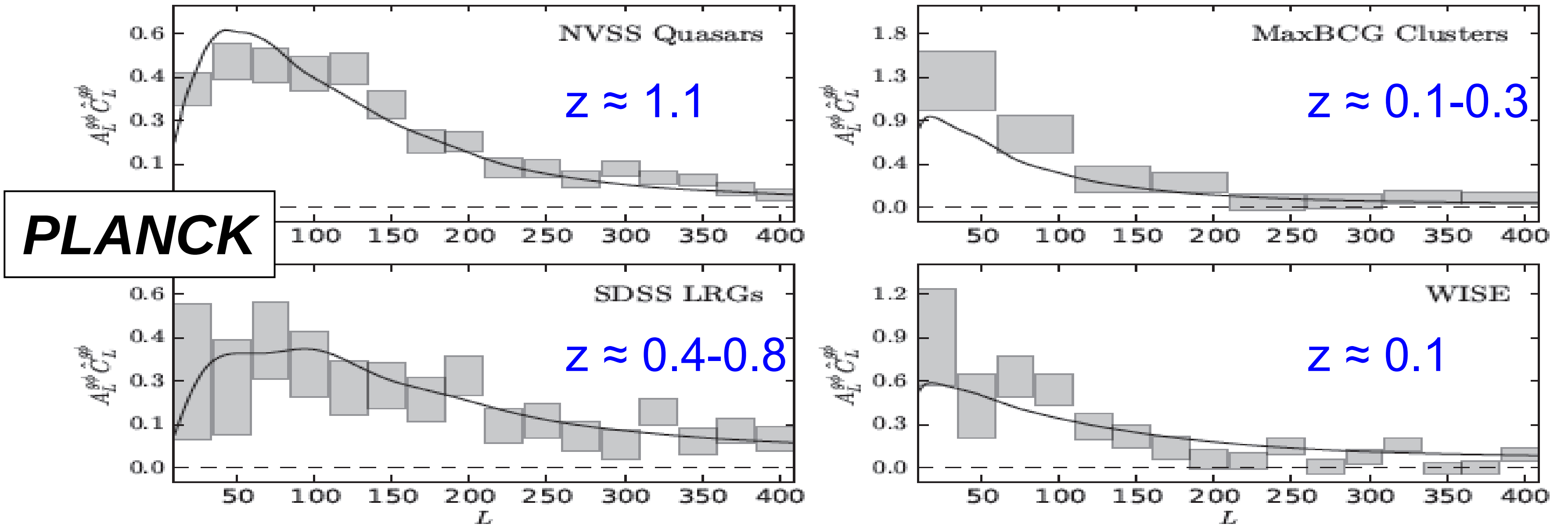


Fig. 17. Cross-spectra of the *Planck* MV lensing potential with several galaxy catalogs, scaled by the signal-to-noise weighting factor $A_L^{g\phi}$ defined in Eq. (52). Cross-correlations are detected at approximately 20σ significance for NVSS, 10σ for SDSS LRGs and 7σ for both MaxBCG and WISE.

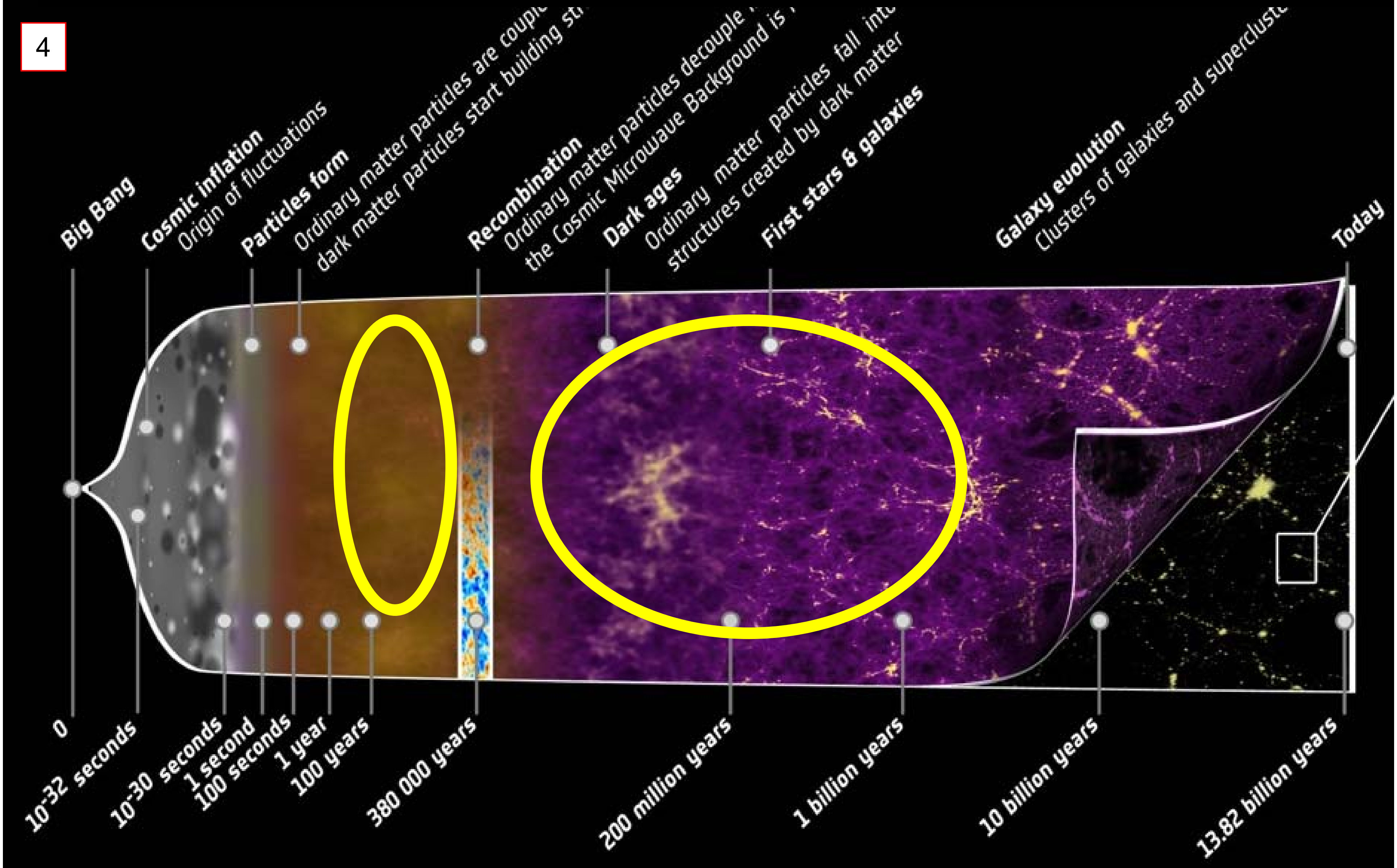
- PRISM will produce sensitive surveys of both gravitational potential and far-infrared galaxies.
- These can correlated, and each of them can be correlated to other tracers, all peaking at different redshifts, obtaining a complete tomography of the universe at high-redshift.

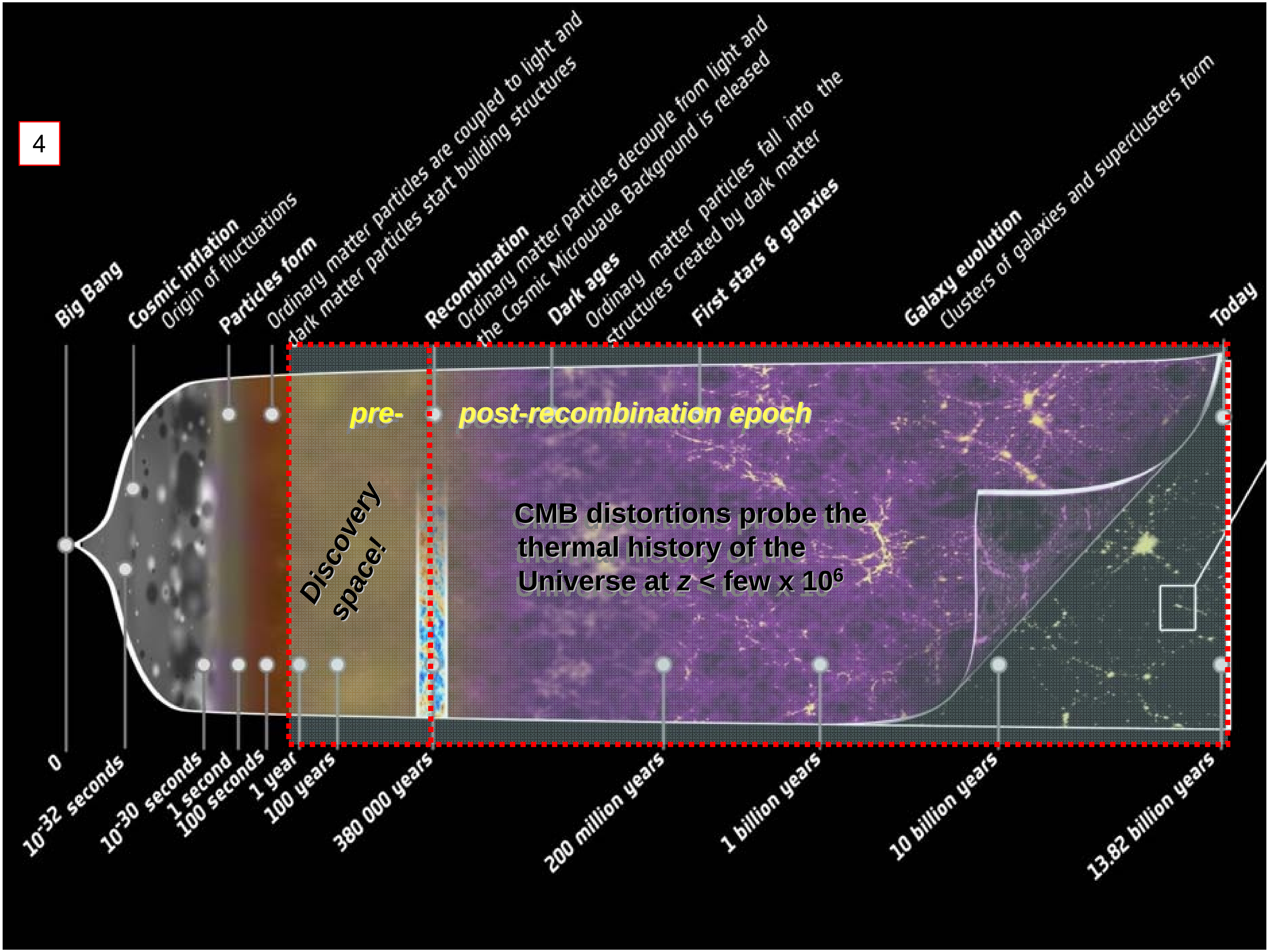
Multi-probe of the Universe
a very powerful combination of :

- Gravitational potential (Lensing, ISW), pointing at dark matter
- Pressure of hot baryons (through tSZ), pointing at primordial gas
- Velocity field (through kSZ), pointing at dark matter
- IR light tracers, pointing at star formation

will allow an unprecedented view of the structures within all our observable Universe (*i.e.* even at z>1)

The pre and post-recombination eras are sampled with different types of spectral distortions of the CMB .





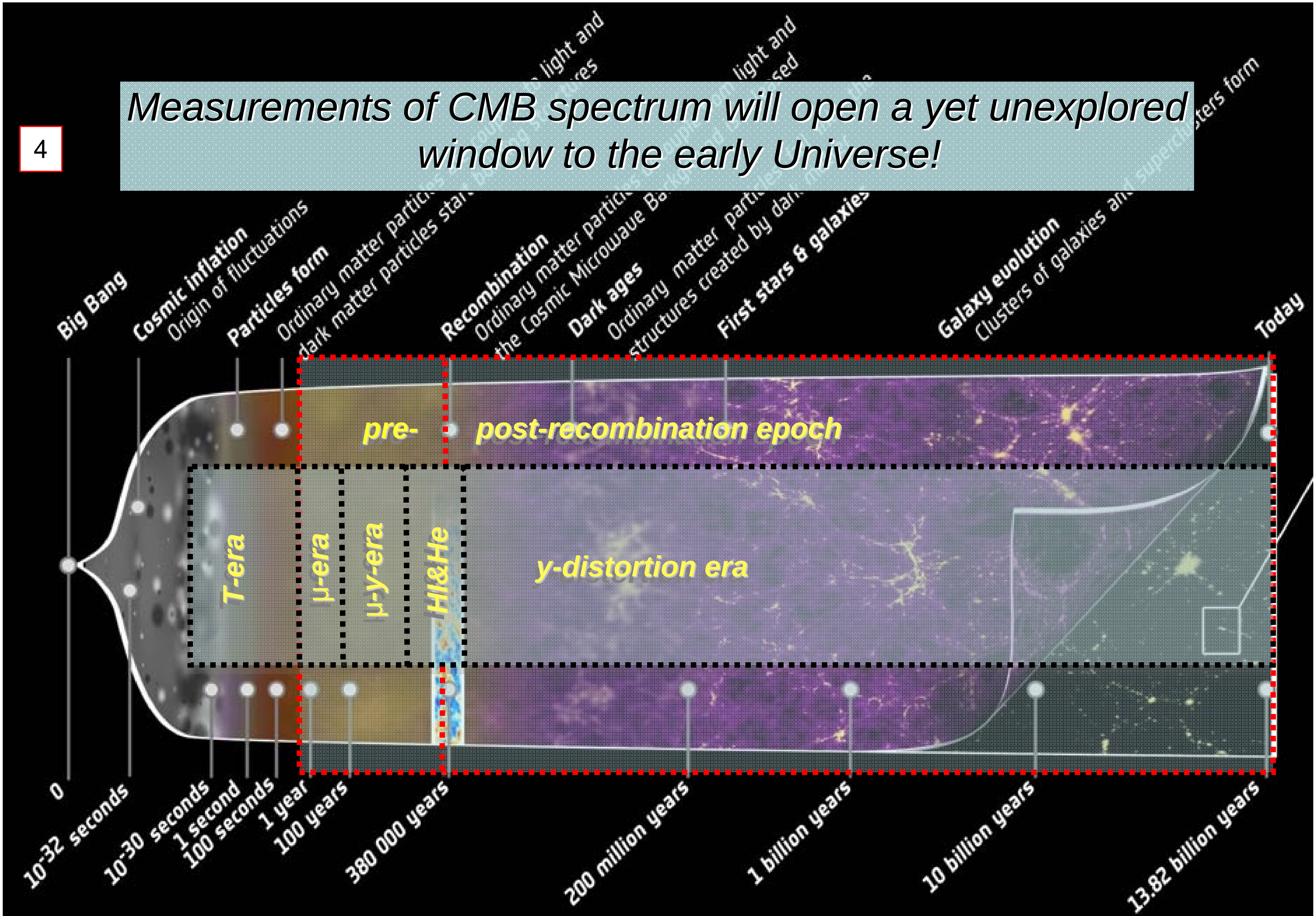
pre-

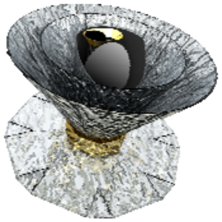
post-recombination epoch

Discovery space!

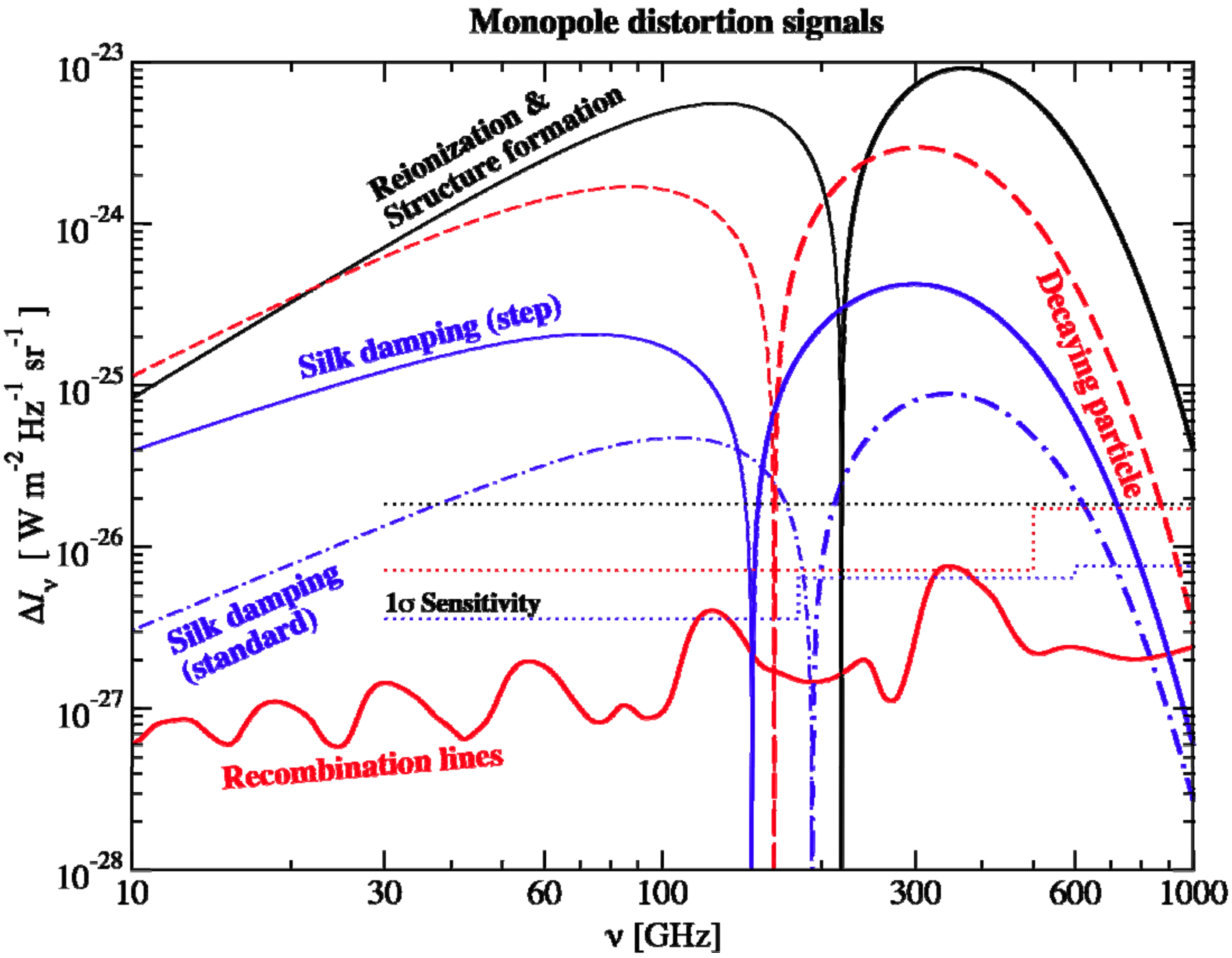
CMB distortions probe the thermal history of the Universe at $z <$ few x 10^6

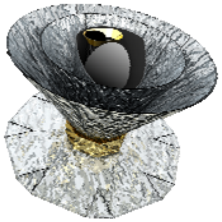
Measurements of CMB spectrum will open a yet unexplored window to the early Universe!





CMB spectral distortions - I





CMB spectral distortions - II

✓ Current observations *consistent with Blackbody & Standard Big-Bang Model*… ***BUT*:**

◆ **Several processes lead to *inevitable* distortions**

❖ *Comptonization & free-free distortion* associated with **reionization / structure formation & hot galaxy clusters**: clearly detectable with ***PRISM*** ($\gtrsim 100\sigma$!)

❖ **Dissipation of acoustic modes** at small scales (1 $\text{Mpc}^{-1} < k < 10^4\ \text{Mpc}^{-1}$):

→ *complementary* probe of *inflation* over additional ~10 e-folds!

→ signal for *standard power spectrum* detectable with ***PRISM***

❖ **Hydrogen and Helium recombination lines from $z \simeq 10^3$**

→ *HI Balmer & Paschen-α lines* detectable with ***PRISM***

→ *additional anisotropic signal* detectable with ***PRISM*!**

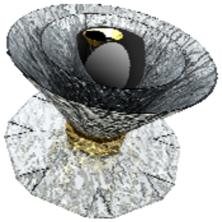
❖ **Resonant scattering signals of metals during the *dark ages***

◆ **CMB spectrum also is a probe of *new physics:* *Discovery potential***

Lifetime and ***abundance*** of *decaying particles* (complementarity with BBN)

❖ Constraints on *annihilating particles* (both from CMB anisotropies & spectrum!)

❖ *Cosmic strings, primordial black holes, primordial magnetic fields, axions...*



CMB spectral distortions - III

◆ **Feasibility/robustness of theoretical studies**

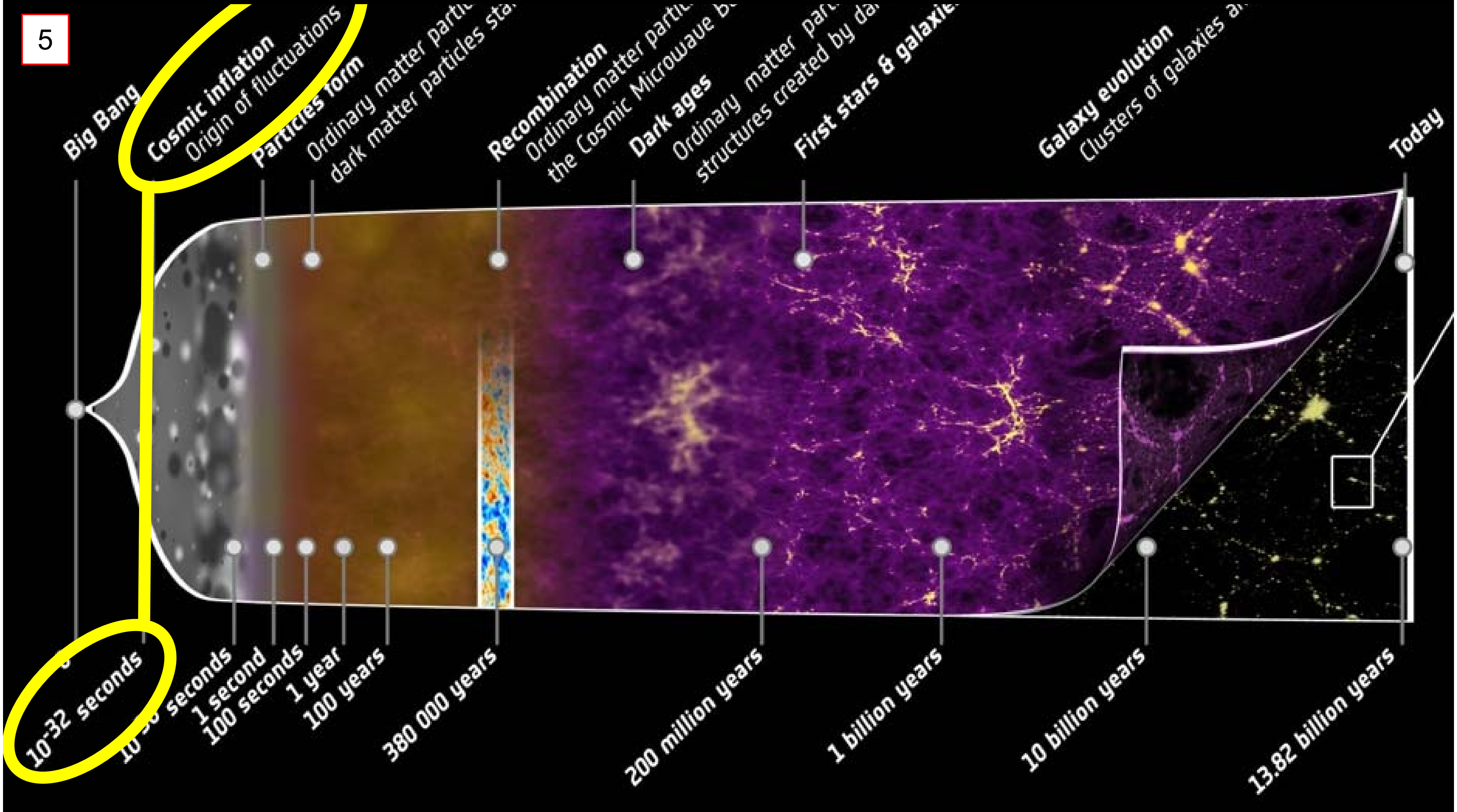
Fast and *accurate predictions* for distortions are possible

- ingest many *physical / astrophysical* processes at both high & low z
- implementations for *different source terms* exist already
- MCMC methods for *comparison with future ultra-precision* data prepared

◆ **“By-products” of absolute temperature high-precision data**

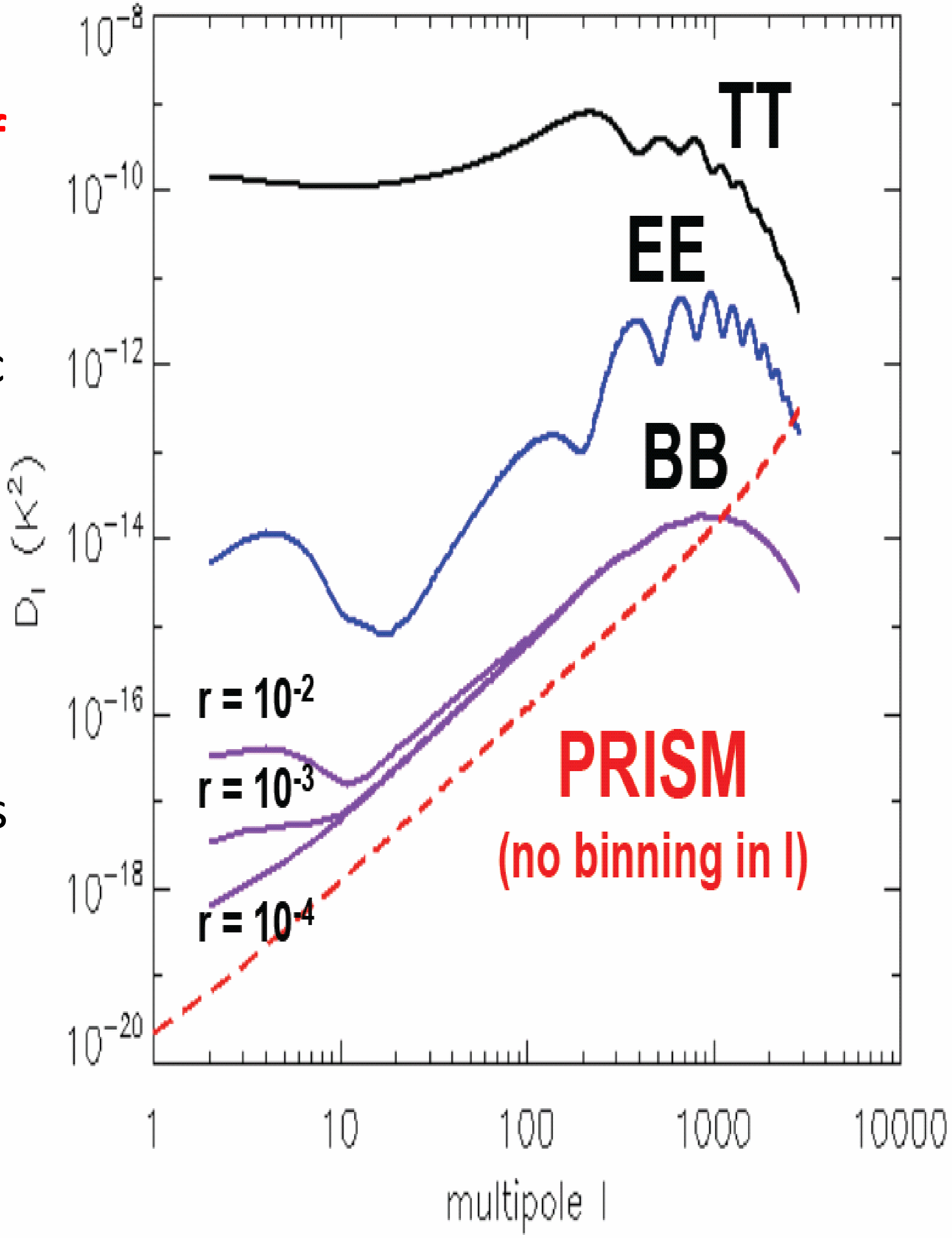
- better *calibration* & *inter-frequency calibration* of *PRISM imager* and all astrophysical microwave/mm/sub-mm data, also of future ground-based facilities (@ higher resolution)
- accurate *assessment of 0-levels* of microwave/mm/sub-mm maps
- crucial link with radio & IR surveys, also for improving *component separation* results by combining *PRISM imager* with *spectrometer*!

Cosmic Inflation (if any) produces primordial density and tensor perturbations
- Tensors produce rotational modes (B-modes) in the CMB polarization field
- Most inflation models predict a slight level of non.gaussianity of fluctuations
- Dissipation of density fluctuations produces distortions in the CMB spectrum



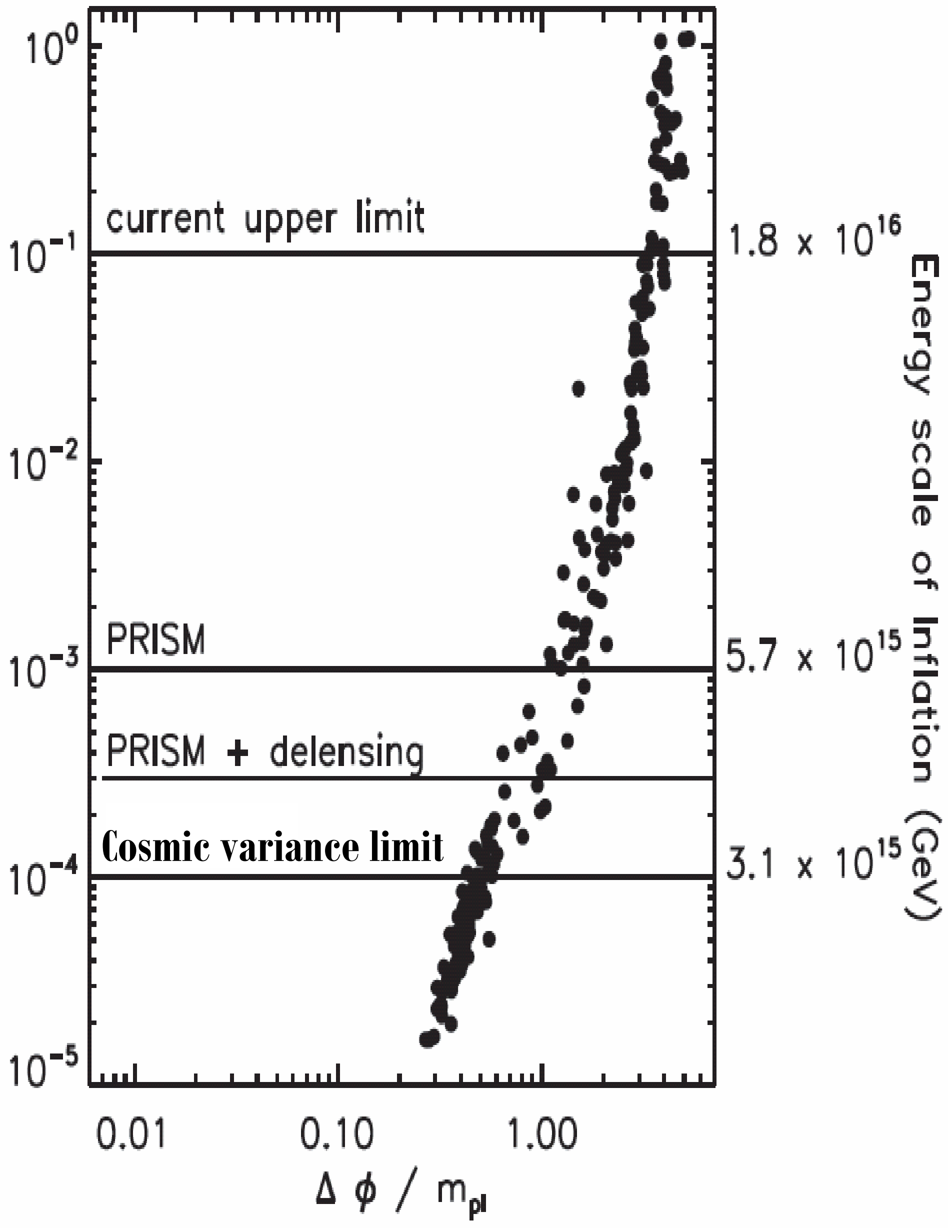
Measuring B-modes

- Measuring B-modes to r=0.001 will require **exquisite control of polarized foregrounds**.
- Current extrapolations with the simplest allowed foreground models predict that the galactic foreground will outshine the r=0.001 primordial by about x100 in all frequency channels, and emission properties are likely to be more complicated than many of the optimistic foreground forecasts suggest
- While forthcoming experiments could find hints of cosmological B modes, **only a large mission with wide frequency coverage and high angular resolution can provide a reliable and convincing detection.**

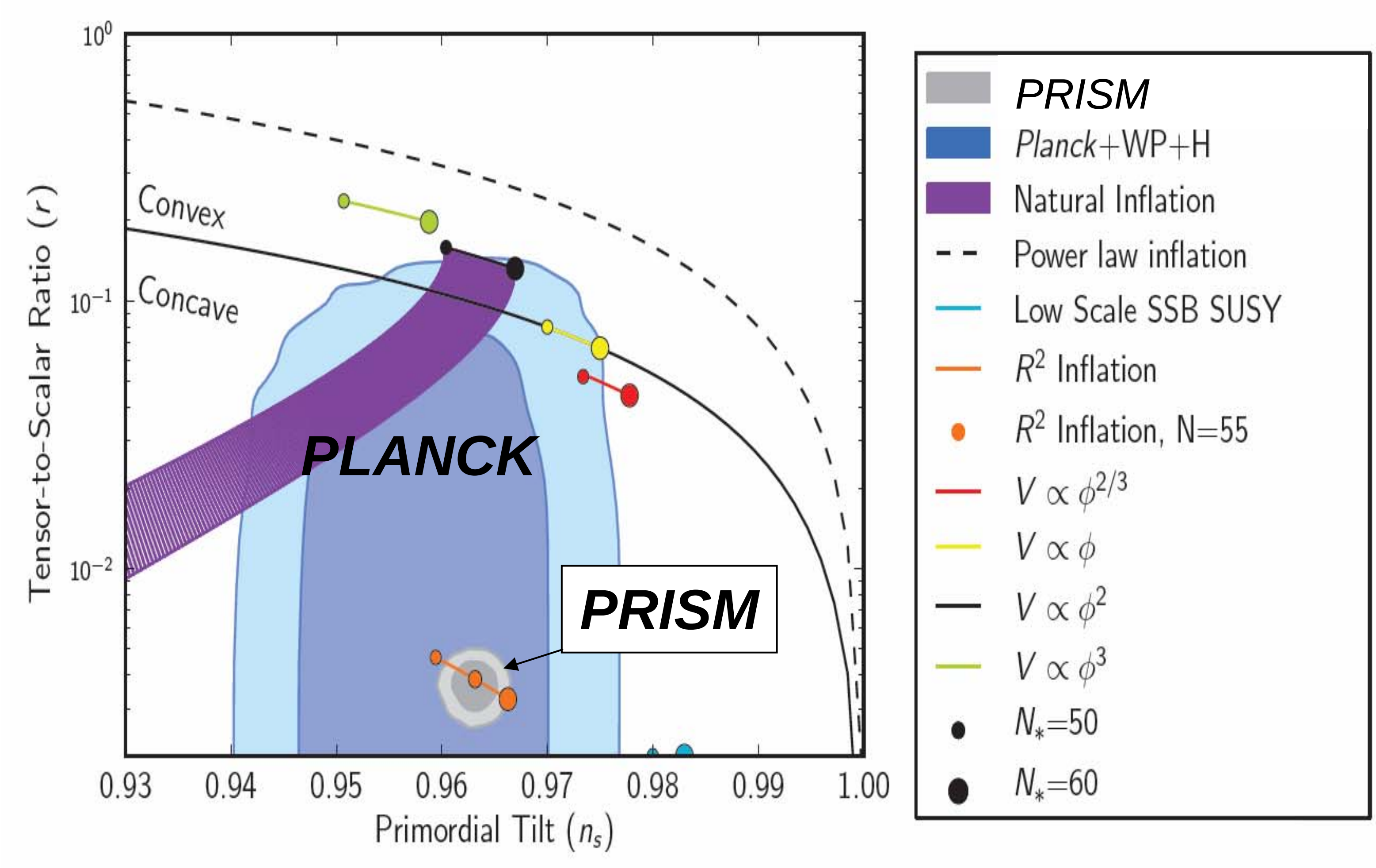


B modes are a unique probe 5 of **new physics near the GUT and Planck scales**

- The generation of primordial gravitational waves with wavelength extending to very large scales near and beyond our horizon is a unique and spectular probe of inflation
- So far only the scalar modes have been detected and characterized, and the energy scale of inflation remain a poorly constrained integration constant
- Presently a key aim of high-energy theory is to construct models of new physics near the Planck scale that include inflation. Knowing the amplitude of the B modes would provide a **new observational constraint of physics in this energy range that CANNOT be probed by any other means**



Comparing Planck vs PRISM constraints on inflation



- The Planck mission has excluded a large number of inflationary models but many others remain. Prism will be able to reduce the parameter space r-n_s by orders of magnitude (grey-region)

Non-Gaussianity

5

- All inflationary models predict a small amount of non-Gaussianity. One of the key PLANCK results was to rule out all the models with large non-Gaussianity proposed by theorists to explain the WMAP hint of f_{NL}~87.
- At present nothing more involved than a simple single scalar field model is needed to satisfy Planck constraints.
- **PRISM will provide the ultimate CMB constraints on primordial non-Gaussianity** thanks to its full-sky coverage and exquisite angular resolution. (Other probes have to rely on uncertain modeling.)

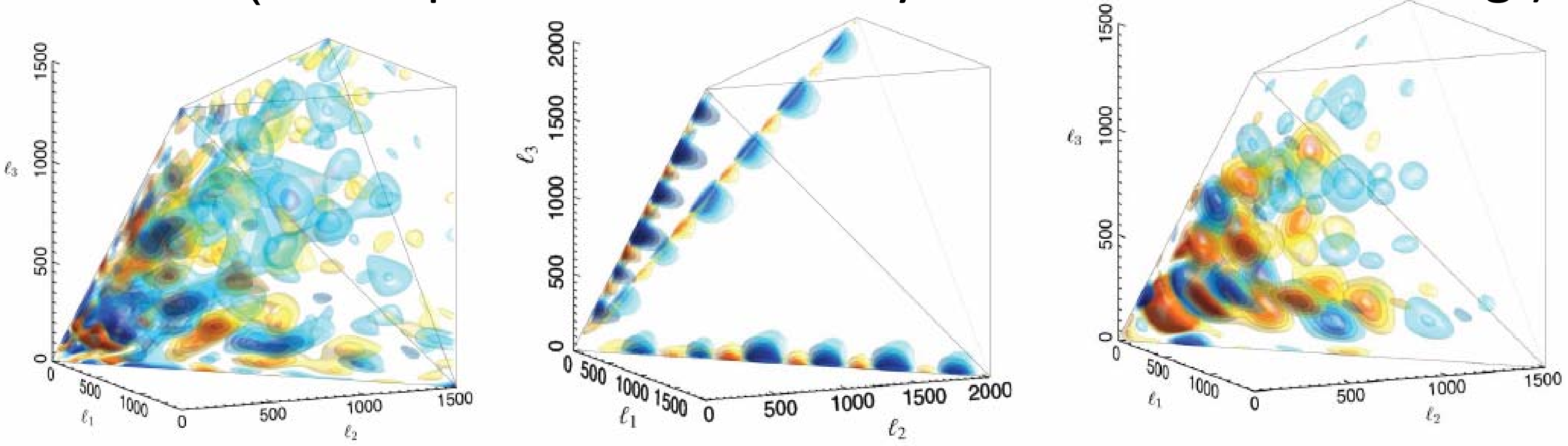
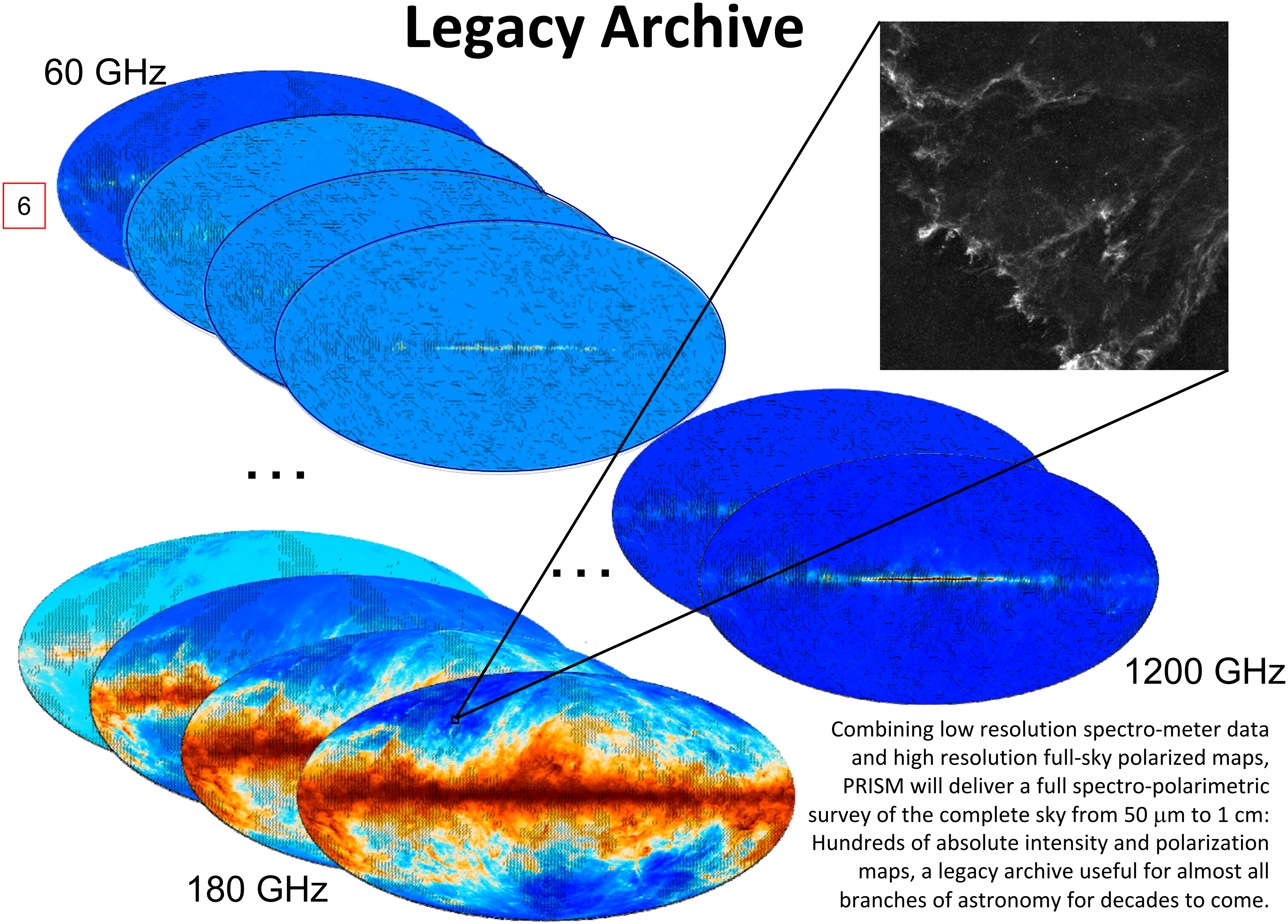


Figure 5: *Planck* CMB temperature bispectrum [84] (left) and primordial (right) and late-time (middle) non-Gaussian shapes [84, 83]. Note the periodic CMB ISW-lensing signal (middle) in the squeezed limit along the edges, which is seen at the 2.5 σ level in the *Planck* bispectrum on the left. Scale-invariant signals predicted by many inflationary models are strongly constrained by the *Planck* bispectrum, although 'oscillatory' and 'flattened' features hint at new physics. A example of an inflationary 'feature' model is shown on the right. PRISM will probe these hints with an order of magnitude more resolved triangle configurations.

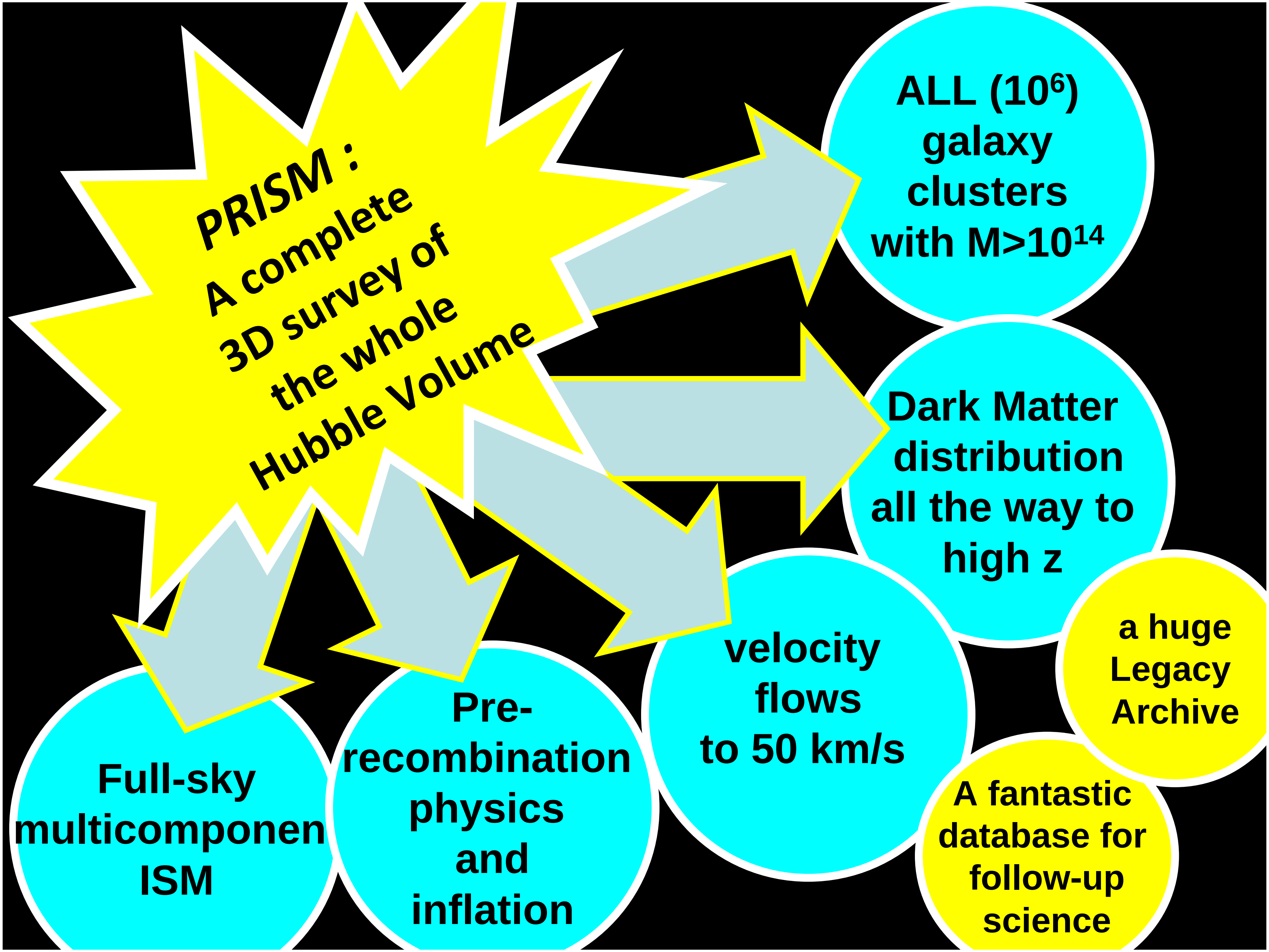
Additional science …

- Non Gaussian perturbations
- Cluster temperatures
- Neutrino masses
- Interacting dark matter
- Decaying dark matter
- CMB Rayleigh scattering
- Modified gravity
- Topological defects
- Zodiacal emission & solar system bodies
- … … …

Legacy Archive



Combining low resolution spectro-meter data
and high resolution full-sky polarized maps,
PRISM will deliver a full spectro-polarimetric
survey of the complete sky from 50 μm to 1 cm:
Hundreds of absolute intensity and polarization
maps, a legacy archive useful for almost all
branches of astronomy for decades to come.



***PRISM* :**

A complete 3D survey of the whole Hubble Volume

ALL (10^6) galaxy clusters with $M>10^{14}$

Dark Matter distribution all the way to high z

velocity flows to 50 km/s

Pre-recombination physics and inflation

Full-sky multicomponen ISM

a huge Legacy Archive

A fantastic database for follow-up science